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CONSULTING GEOTECHNICAL AND MINING ENGINEERS

STUDY TO INVESTIGATE THE PROBLEM OF ATMOSPHERIC FOGGING IN UNDERGROUND MINES

FINAL REPORT

BY

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SUMMARY

Fog occurrences in underground mines may create hazardous conditions and a reduction or loss of production. Fog probably occurs in most mines to a greater or lesser degree and typically has been considered to be a nuisance which is tolerated, or results in rescheduling of production to non-fogged areas of the mine.

Fogs are usually created in supersaturated conditions by moisture droplets forming on atmospheric particles known as cloud condensation nuclei. Fog classification systems are discussed and all mine fogs will class as very dense fogs in meteorological terms, i.e. less than 100 m visibility.

Fog formation in underground mines may generally be caused by:

- (a) cooling of air to the saturation temperature;
- (b) addition of water and water vapour to the air;
- (c) change of barometric pressure;
- (d) mixing of moist air systems at different temperatures.

Mines in Arctic or severe winter climates may experience ice fogs but all other fogs experienced by mines may be classified as warm fogs.

A survey was conducted on the occurrence of fog in underground mines across Canada by contacting various Mine Inspectors and safety organizations. A questionnaire was sent out and three mines were visited to examine the problem first hand.

The principal technique for preventing fog in underground mines is good ventilation planning. Naturally, this is easier to achieve when designing a new mine layout, on condition that the potential for excessive fog formation has been recognized. Based on surface meteorological data and underground temperature predictions, a suitable ventilation design may be prepared for minimizing for occurrences.

It is not easy to deal with fog in existing mines where alteration to ventilation systems may require considerable capital outlay. Various methods to prevent the formation of fog were analyzed. Systems considered were:

- Heating of air
- Raising barometric pressure of air
- Addition of drier air to saturated air
- Removal of moisture from air by drying

Various methods of implementing the above systems and their cost were considered, including direct heating, fan compression, mixing of air streams, mixing with compressed air, refrigeration machines, absorbents, adsorbents, settling out of droplets in vertical and horizontal airways and eliminators.

Cost comparisons were made for a life of 5 years and of 10 years for direct heating, refrigeration (i.e. cooling and reheating), and fan compression. Other methods such as air stream mixing could not be compared as their costs are site dependant. For most Canadian conditions where one is typically dealing with the removal of 0.5 g/kg of liquid moisture, direct heating appears to be the most attractive. Fans would be suited for areas where liquid water content remained constant as their operation is inflexible. Coolers/reheaters will have limited application because of their complexity and relatively high capital cost but should be considered for areas where the liquid moisture content consistently approaches 2 g/kg of air over a large period of the year.

Visibility may be improved in foggy areas by the use of painted stripes on sidewalls, reflectors and fog lights in critical locations. Vehicle speed and passage should be controlled to prevent accidents due to poor visibility.

A listing of a psychrometric chart program has been included to aid in psychrometric air property determinations.

Finally, suggestions are made for future areas of research into the problem.

RESUME

Le brouillard dans les mines souterraines peut créer des conditions hasardeuses ainsi qu'une réduction ou une perte de production. Il y a probablement plus ou moins de brouillard dans la plupart des mines et on le considère généralement comme un ennui qui est toléré ou qui résulte en mouvement de production vers les coins non embrouillés de la mine.

Le brouillard a habituellement lieu dans des conditions sursaturées et est généralement causé par des gouttelettes d'humidité qui se forment sur des particules atmosphériques connues sous le nom de nucléus de condensation de nuage. Les systèmes de classification du brouillard sont discutés et tous les brouillards de mines sont classifiés comme brouillards très denses en termes météorologiques, c.-à.-d. moins de 100 m de visibilité.

La formation de brouillard dans les mines souterraines peut généralement être causée par:

- (a) le refroidissement de l'air jusqu'à la température de saturation;
- (b) l'addition d'eau et de vapeur d'eau à l'air;
- (c) un changement de pression barométrique;
- (d) un mélange de systèmes d'air humide à des températures différentes.

Les mines situées dans l'Arctique ou dans des climats très froids peuvent avoir du brouillard de glace mais tous les autres brouillards de mines peuvent être classifiés comme des brouillards chauds.

On a mené une enquête sur le brouillard dans les mines souterraines à travers le Canada en communiquant avec divers inspecteurs de mines et organismes de sûreté et de sécurité. On a envoyé un questionnaire et on a visité trois mines pour examiner le problème sur place.

La technique principale pour empêcher le brouillard de se former dans les mines souterraines est une bonne planification du système d'aérage. Naturellement, il est plus facile de le faire en dessinant une nouvelle mine à la

condition que le potentiel de formation excessive de brouillard ait été reconnu auparavant. En se basant sur les données météorologiques de surface et sur les prédictions des températures souterraines, on peut concevoir et créer un système d'aérage adéquat pour diminuer le brouillard.

Ce n'est pas facile de faire face à ce problème de brouillard dans les mines existantes où une modification des systèmes d'aérage peut requérir de grosses dépenses. On a analysé diverses méthodes pour empêcher la formation de brouillard. Les systèmes qui ont été considérés sont:

Le chauffage de l'air

La hausse de pression barométrique de l'air

L'addition d'air plus sec à l'air saturé

L'enlèvement de l'humidité de l'air par un procédé de séchage.

On a également considéré différentes méthodes pour mettre en oeuvre les systèmes ci-haut mentionnés, y compris le chauffage directe, la compression par ventilateur, le mélange de courants d'air, un mélange avec de l'air comprimé, des machines frigorifiques, des produits d'absorption, le dépôt de gouttelettes dans des voies d'aérage verticales et horizontales et des produits éliminateurs.

On a fait la comparaison des coûts pour une vie de 5 ans et une vie de 10 ans de systèmes de chauffage directe, de systèmes de réfrigération (c.-à.-d. refroidir et réchauffer) et des systèmes de compression par ventilateur. On ne pouvait pas comparer certaines autres méthodes telles que le mélange de courants d'air car les coûts dépendent de l'endroit. Pour la plupart des conditions au Canada où l'on doit enlever 0.5 g/kg d'humidité liquide, le chauffage direct semble la meilleur alternative. Des ventilateurs seraient adéquats pour les endroits où la teneur d'eau liquide demeure constante car leur fonctionnement ne donne aucune flexibilité. Le méthode de refroidissement/réchauffage n'a qu'un usage limité à cause de la complexité des pièces de machinerie requises et le coût relativement élevé en capital mais elle devrait être considérée pour les endroits où la teneur d'humidité liquide approche consistemment 2 g/kg d'air pendant une grande partie de l'année.

On peut améliorer la visibilité dans les endroits sujets au brouillard au moyen de rayures peintes sur les parois latérales et l'usage de réflecteurs et de phares anti-brouillard dans les endroits les plus importants. On devrait

également contrôler la circulation de véhicules et leur vitesse afin de prévenir les accidents causés par une mauvaise visibilité.

Une liste imprimée d'un programme de tableau psychrométrique est jointe pour aider à déterminer les propriétés de l'air de façon psychrométrique.

Finalement, on suggère des domaines appropriés de recherches sur ce problème pour l'avenir.

1.0 INTRODUCTION

1.1 General

Atmospheric fog is found in several underground mines in Canada and other countries. The effects of such fog is to reduce visibility which can directly or indirectly contribute to accidents and production losses. The fog is often mistaken for fumes or dust by employees and this can result in complaints being made to management and a lowering of employee morale.

Fog in Canadian mines often results from saturated surface air being compressed by a fan at the mine intake and circulated through the mine by an ascensional ventilation system. The air expands and cools as it ascends and is further cooled by heat transfer to rock if it is at a lower temperature. This results in supersaturation as the air temperature falls and condensation occurs using dust particles as condensation nuclei.

The amount of liquid water present in Canadian mine fogs is typically 0.5 g/kg with ratios of up to 3.0 g/kg under very humid surface conditions, particularly in late spring and early summer. These water contents may result in visibilities of less than 10 m and necessitate closure of stopes and haulage roads because of insufficient visibility. Less severe fogs impair mining operations and are typically tolerated as a nuisance about which little can be done.

1.2 Scope

This report contains the results of CANMET project No. OSQ82-00091 "Study to Investigate the Problem of Atmospheric Fogging in Underground Mines".

The objectives of the project were to:

- (a) review and detail the existing techniques to deal with the problem of foggy atmosphere;
- (b) survey and analyse the fogging atmospheric problem in Canadian mines;
- (c) describe the techniques to control the fogging atmosphere suitable for Canadian mines;
- (d) analyse in detail the fogging atmospheric problem and its control in four or five typical Canadian underground mines;
- (e) estimate the capital and operating cost associated with the system used for the control of fogging atmospheres in mines.

Metric units have been used throughout the report and a conversion table is included in Appendix IV.

2.0 FOG

2.1 General Considerations

Atmospheric fogging causes light extinction which affects visibility. The problem of reduced visibility has been studied extensively by meteorologists to determine fog formation mechanisms and classification systems. Much of this research has been conducted on behalf of the transportation industries and military services. A review of this research was undertaken to determine its application to fogging in underground mines.

2.2 Meteorological Considerations

Atmospheric fog formation may be described by the disciplines of thermodynamics, cloud physics, boundary layer theory and particle motion. However, no fully standardized classification system exists (Jiusto, 1981) but there are several systems that have wide acceptance.

Willett (1928) devised a fog classification system which was augmented by Byers (1959). More than 15 fog types exist but they can be classed into four main groups:

- (a) radiation fogs
- (b) frontal fogs
- (c) advection fogs
- (d) ice and snow fogs.

Fogs are usually created in supersaturated conditions by moisture droplets forming on atmospheric particles known as cloud condensation nuclei. These particles were identified by John Aitken between 1880 and 1916 and were divided into two groups (Mason, 1962):

- (i) hygroscopic - particles on which condensation can occur below saturation (100 per cent relative humidity); and

- (ii) non-hygroscopic - particles which require the atmosphere to be supersaturated (with 100 per cent relative humidity and free liquid water droplets) for condensation to occur.

Such condensation normally results from one of a mixture of four major processes:-

- (a) cooling of air to saturation (dewpoint) temperature
- (b) addition of water and/or water vapour to the air
- (c) change in barometric pressure
- (d) mixing of moist air systems at different temperatures.

Radiation fog forms due to steady cooling of air close to the ground until the saturation vapour pressure is exceeded.

Frontal fogs result from an increase in moisture due to falling of rain from high, relatively warm layers into cooler, dryer air below.

Advection fogs result from the mixing of two or more systems of moist air at different temperatures; for this reason, they are sometimes called mixing fogs.

Ice fogs are associated with intense surface inversions. They are formed by strong radiational cooling which precedes the fog. This can occur at temperatures close to -20°C , but more frequently is associated with surface temperatures below -30°C .

Fogs with temperatures exceeding 0°C are called "warm fogs" by meteorologists.

2.3 Fog Intensity and Classification

Fog intensity is normally described by the visibility or horizontal visual range. Weather stations use both human and automated measurements.

Typical human methods are the observation of targets set at various distances from the observer. The targets are usually black and white concentric rings and visibility is determined as the point at which the observer is just unable to distinguish the contrast between the black and white rings. Naturally, this is dependent to a large extent on the visual acuity of the observer which will vary from person to person.

Electronic instruments are also used to determine visual range and they may very simply be classified into two types. The first is a single instrument with a light source which measures the amount of back scatter from the light penetration of the fog, and the second which has two components with a light source and a receiver which measures the intensity of light received from the source. Various forms of the instruments are available commercially.

It is recommended that for underground determination, the human method be used and a suitable target illuminated by a cap lamp should be moved away from the observer until it is not possible to contrast the black and white circles on the target.

Intensity definitions are not standardized, although the internationally accepted definition of fog is "a condition where visibility is less than 1,000 m".

Haze is made up of particles, either in a dry state or, more usually, as water droplets formed on hygroscopic condensation nuclei. The particle size and composition varies from region to region depending on local conditions. Blue and air pollution hazes have particle radii usually from 0.1 to 0.3 μ m whilst grey haze, which results from pollen, spores, natural salt particles and similar materials, has particle radii from 5 to 30 μ m. Such large particles have a high settling velocity and the haze disperses faster than smaller particle haze. Air pollution hazes are extremely hygroscopic.

Droplets will form on hygroscopic particles at a particular value of relative humidity dependent on the particle's chemical composition. This is known as the deliquescence point. Jiusto (1981) reports that due to urbanisation and a greater atmospheric concentration of hygroscopic pollutants, the critical humidity for haze formation has decreased and hazes are now evident at relative humidities as low as 50 per cent instead of the 70 to 75 per cent previously considered necessary.

Jiusto recommends the classification of fogs and haze as set out in Table 2-1 for general use by meteorologists. It is readily seen from the table that significant atmospheric fog in underground mines will always be classed as a very dense fog in meteorological terms because visibility will be less than 100 m.

Cloud condensation nuclei (CCN) have a major effect on fog droplet formation. The total number of drops formed and their size distribution depends on the total number of CCN per unit air volume, the size distribution of the CCN, their chemical composition and the supersaturation at which the CCN start to form droplets. Dust particles from air pollutants result in more numerous and smaller droplets than in clean air and consequently poorer visibility. Atmospheric aerosols cover a wide range of particle sizes from 10^{-4} μ m radius for small ions to more than 10 μ m for the largest salt and dust particles.

Mason (1962) defined three classes of nuclei:

- (i) Aitken nuclei from 5×10^{-4} μ m to 0.2 μ m radius
- (ii) Large nuclei from 0.2 to 1 μ m radius
- (iii) Giant nuclei having radii greater than 1 μ m.

Aitken nuclei can have concentrations exceeding 1 million/mL in industrial cities. However, their mass concentration is usually below 10 μ g/m³ which makes them difficult to separate, analyze chemically and identify. Such small particles can have considerable effect in contributing to light extinction in dense fog.

TABLE 2-1
Fog Classification - Jiusto, 1981

Category	Visual Range
Very dense fog	< 100 m
Dense fog	< 400 m
Fog	< 1,000 m
Light fog	1 to 5 km
Dense haze	> 5 to 10 km
Light haze	> 10 to 15 km

The liquid water content of a fog is inversely proportional to the visual range and provides a direct indication of fog intensity. Values of liquid water content vary from a few mg/kg to peak values of 0.36 g/kg which are seldom exceeded in surface fogs. This is in contrast to deep mine return air systems where liquid water contents of as much as 14.5 g/kg may exist at exhaust fans.

The relationship between visual range and liquid water content is found using the Koschmieder equation:

$$V = 3.912/G$$

where:

V = visual range in kilometres

G = light extinction due to particle scattering and absorption.
(see later for determination of G)

By multiplying numerator and denominator of the Koschmieder equation by the liquid content, one obtains the Trabert equation:

$$V = \frac{2.6 k \times r \times w}{Lwc}$$

V = visual range in metres

r = drop radius (μ m)

Lwc = liquid water content g/kg

k = a variable between 1 and 3 depending on the width of the droplet spectrum

w = air density kg/m³

Drummond (1972) gave a method of determining liquid water contents in mine ventilation air.

Chylek (1978) has developed an approximation formula linking light extinction and liquid water content in the above equations.

$$S = 128 (Lwc)$$

The equation holds best for fogs whose largest drops do not exceed about 28 μ m diameter (Jiusto, 1981). Therefore, for a fog with liquid water content of 0.36 g/kg at sea level density of 1.2 kg/m³, visual range would be:

$$\frac{3.912}{128(0.36)} \times 1,000 \times 1.2 = 101.9 \text{ m}$$

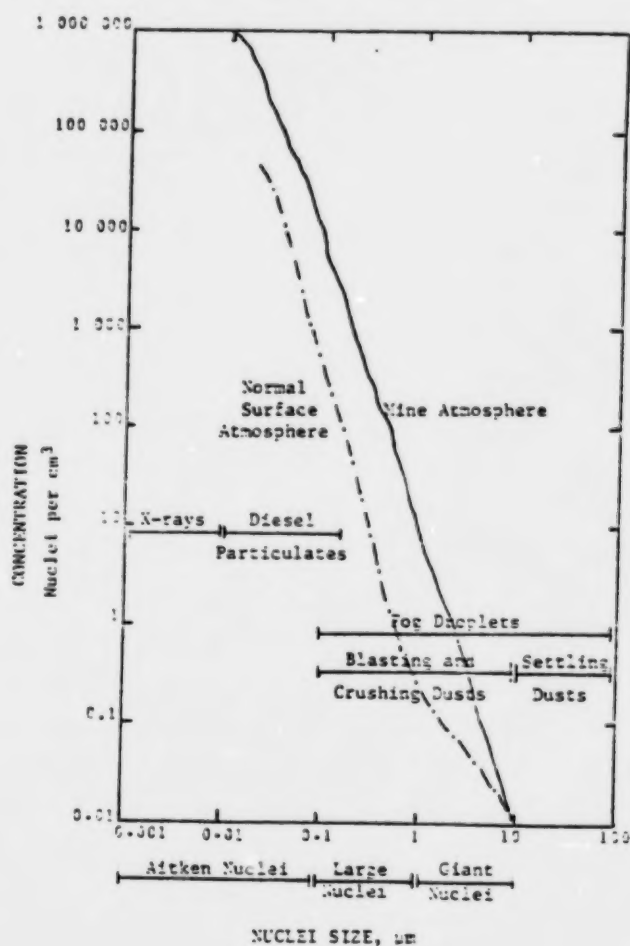
Fog drop spectra have wide variety in size, amplitudes and modes. It is essential to distinguish between the fog and haze droplet populations to determine the degree of light extinction. More data is required according to Jiusto before refined generalizations can be made.

Gillies and Schimmelpfennig (1982) report the work of several investigators which show a classification of particulate matter for surface and mine atmospheres (Figure 2-1). They use the term "Aitken nuclei" for particles smaller than 0.1 μ m, which was given by Ross (1972). This definition differs slightly from that of Mason (1962) as it excludes particles from 0.1 to 0.2 μ m in size. Large nuclei are classed as those between 0.1 and 1 μ m in size. Ross (1972) stated that the chemical make up of the Aitken particles can affect the stability of a fog when the particles adhere to water droplets already present. Ross (1972) and Mercer (1973) found that when Aitken particles collide they often adhere together or coagulate. Rogers (1976) stated that the high concentration levels in the atmosphere for Aitken particles do not lead directly to fog formations.

Green and Lane (1957) consider the large nuclei of 0.1 to 1 μ m radii as the major source of condensation nuclei and are responsible for

**CONCENTRATION OF ATMOSPHERIC NUCLEI
AGAINST SIZE FOR NORMAL SURFACE AIR
AND MINE AIR.**

Figure 2-1



After Gillies and Schimmelpfennig (1982).

the majority of surface atmospheric fog formation. They found that surface air under normal conditions will contain approximately 100,000 Aitken nuclei/mL and 5 to 200 large nuclei/mL. Even these large nuclei have low settling velocity (0.1 m/hour) and will remain suspended for long periods of time.

The giant atmospheric nuclei, larger than $1\text{ }\mu\text{m}$ radii, are considered to be responsible to some extent for the initiation of fogging. However, under normal surface atmospheric conditions, the concentration of giant nuclei has been measured as approximately 1/mL. Such particles are therefore not present in the same quantities as the 0.1 to $1\text{ }\mu\text{m}$ particles and do not have the same influence on fog formation. Giant particles are rare in surface atmospheres because of their high settling velocity which exceeds 2.5 m per hour.

Concentrations in underground mines are significantly larger than these concentrations for all nuclei and particle sizes and this affects the initiation of fogging.

The meteorological treatment of fog may now be examined for application to atmospheric fogging in underground mines.

2.4 Atmospheric Fogging in Underground Mines

The methods of fog formation in underground mines are similar to the meteorological systems:

(a) Cooling of air to saturation temperature

This is a common occurrence when warm air is passed through airways with surface rock temperatures lower than the air dry bulb temperature. Heat is transferred from the air to the rock and the relative humidity of the air increases until it is saturated to 100 per cent relative humidity. Further

cooling results in liquid water droplets being formed on particles in the air and these droplets create a fog which is carried by the air velocity.

(b) Addition of water and water vapour to the air

Water sprays can result in air becoming saturated. If excess water is sprayed and the air velocity is high enough, then a mist of liquid water will be carried downstream from the sprays. Moisture may be picked up from water bearing fissures, uncovered ditches, diesel exhaust water scrubbers and accumulations of water.

(c) Change of barometric pressure

Air passing through a downcast vertical shaft will increase in pressure due to the increasing weight of the column of air above it as the depth increases. This effect is known as auto-compression and results in heating of the air.

The reverse effect is experienced when air ascends from deep to shallow working areas or to a surface exhaust point. The weight of the air column decreases as the air rises and the air pressure will decrease by approximately 1 kPa/100 m decrease in depth below datum. The decompression or expansion cools the air and the dry bulb temperature will decrease by 1°C/100 m and the wet bulb temperature by 0.5°C/100 m decrease in depth. Because the dry bulb temperature decreases faster than the wet bulb temperature, it is possible for unsaturated air to become saturated if the two temperatures decrease to the same value as the air ascends.

For example, air entering an airway at 110 kPa pressure and with wet bulb temperature 10°C and dry bulb temperature of 12°C at a depth of 500 m will experience the changes in properties shown in the following table as it ascends:

Depth (m)	Barometric Pressure (kPa)	Wet Bulb (°C)	Dry Bulb (°C)	Relative Humidity (%)
500	110	10.0	12.0	77.4
400	109	9.5	11.0	82.4
300	108	9.0	10.0	87.8
200	107	8.5	9.0	93.7
100	106	8.0	8.0	100.0

It is seen that the air becomes saturated at a depth of 100 m and that the relative humidity of the initially unsaturated air increases as the depth and barometric pressure decrease.

If the surface is at an elevation of 0 m, the saturated air ascending through the next 100 m will undergo further cooling and become supersaturated. Water droplets will form in the air due to the presence of dust and other particles which act as condensation nuclei. The droplets may fall back down the airway if the air velocity is less than 7.5 m/s or will be carried up by the air stream if the velocity exceeds 12.0 m/s. At intermediate air velocities, a fog cloud will form and remain suspended in the airway as described by Lambrechts (1956).

Fog formation of this type is common in gold mines in South Africa, and Barenbrug (1974) reports a 1210 m deep upcast shaft in which the liquid moisture content of the air increases from 0 g/kg at the shaft bottom to 2.8 g/kg at the surface fan drift.

(d) Mixing of moist air systems at different temperatures

Compressed air exhausted from pneumatic equipment has a low temperature, often about 1°C, because of cooling caused by

expansion. This cold dry air coming into contact with moist warm ambient air cools the ambient air which results in localized liquid water condensation. This creates the "fogging" effect at pneumatic machinery exhausts. Air streams of different temperatures and humidities may mix in underground airways and cause localized fogging if the mixture becomes supersaturated. This effect has been reported by Granduc Mines, British Columbia.

2.5 Condensation Nuclei

Gillies and Schimmelpfennig (1982) measured the particle concentrations in underground mines in the Ozark Lead Mine, Missouri. The results are shown in Figure 2-1. It is apparent that the concentrations of Aitken nuclei are considerably higher underground than on surface. Measurements of 4,200 nuclei/mL are reported for surface, compared to 136,000 nuclei/mL underground. Local concentrations of about 1 million nuclei/mL were recorded in air near where diesel equipment was operating. Diesel equipment causes a significant increase in the concentration of Aitken nuclei and Table 2-2 shows the effects measured at the Ozark Lead Company, Missouri.

The authors report that concentrations of 2 or 3 particles/mL is normal for particles between 0.5 and 0.7 μ m in size in surface air. Giant nuclei are expected to be present at concentrations of 1/mL in such air. The underground measurements at Ozark gave concentrations of 6 to 12 particles of size 0.5 to 0.7 μ m and 50 to 80 particles/mL between 1 and 5 μ m in size.

Konimeter counts in Canadian metal mines indicate that concentrations of 100 to 200 particles/mL would be normal levels of respirable (sub 5 μ m) dust present in underground air. These figures would also be typical of South African dust measurements in gold mines.

TABLE 2-2

Increase In Aitken Nuclei When
Diesel Equipment Was Operating Nearby

Concentration of Nuclei Without Diesel Equipment (nuclei/mL)	Concentration of Nuclei With Diesel Operating (nuclei/mL)	Increase (%)
78,000	450,000	580
110,000	310,000	280
165,000	1,700,000	970
150,000	390,000	260

Since the large and giant nuclei form the major source of condensation nuclei for the formation of water droplets, it is apparent that there are always sufficient condensation nuclei available in underground mines for fog droplet formation.

2.6 Classification of Mine Fogs

Atmospheric fogging in mines is only significant if visibility is reduced and, for this reason, only fogs of visual range less than 100 m can be considered significant. All mine fogs therefore class as very dense fogs in meteorological terms.

Echo Bay Mines - Lupin Operation in the North West Territories report the occurrence of ice fogs during very cold weather with surface temperatures from -20 to -50°C. All other fogs experienced by mines can be classified as warm fogs.

2.7 Visibility

It is apparent that if a liquid water content of 0.36 g/kg results in a visual range of 102 m, then larger water contents will reduce the visual range. Table 2-3 shows the estimated visual ranges for possible underground fog liquid water contents, using the Koschmieder and Chylek equations. It is readily seen that even smaller supersaturations will result in significant fogs in underground mining.

Conditions at the top of deep upcast shafts such as those reported by Barenbrug would result in visibilities of 10 m and less depending on the available illumination. The liquid water content of mine exhaust air may exceed 5 g/kg and the figures determined by Lambrechts (1956) are set out in Table 2-4. The maximum liquid water content of 14.5 g/kg shown on the table would correspond to a visual range of 2.1 m, which would pose very serious problems when personnel are required to work inside the fan drift.

TABLE 2-3

Visual Ranges for Varying Liquid Water Content
from the Koschmieder and Chylek Equations

Liquid Water Content (g/kg)	Visual Range (m)
0.5	73.4
1.0	36.7
1.5	24.5
2.0	18.3
2.5	14.7
3.0	12.2
4.0	9.2
5.0	7.3
10.0	3.7
15.0	2.4

TABLE 2-4

Liquid Water Content in Upcast Shafts
Reported by Lambrechts (1956)

Shaft	Depth (m)	Air Quantity (m^3/s @ density = $1.0 \text{ kg}/\text{m}^3$)	Water Removed From Fan Drift (L/s)	Liquid Water Content (g/kg)
Springs Joint Ventilation Shaft	975	496	0.88	1.8
E. Daggafontein May Shaft	1,189	335	1.26	3.8
President Steyn No. 1	1,280	196	0.61	3.1
President Steyn No. 2	1,402	201	0.91	4.5
President Brand No. 1	1,402	205	1.89	9.2
President Brand No. 2	1,402	191	2.78	14.5
Western Holdings No. 1	1,311	201	1.89	9.4
Western Holdings No. 2	1,311	217	1.77	8.2
Free State Geduld No. 1	1,615	219	1.83	8.4
Free State Geduld No. 2	1,554	179	0.95	5.3
Lorraine No. 1	1,615	144	0.13	0.9
Lorraine No. 2	1,615	230	0.81	3.5

Supersaturation measured during mine visits and from questionnaires indicate that much lower values are experienced in Canadian mines. Typical values encountered in these mines were 0.5 to 3.0 g/kg of liquid water in air which represent the visual ranges of 73 m and 12 m, respectively. Visibilities appeared to be considerably less for underground conditions than they would be for the same liquid water content on surface, because of the reduced light levels. The visibilities were subjective depending on background lighting and it is recommended that the procedure of measuring visibility, as outlined earlier in the chapter, be adopted as a standard and used for comparison purposes.

2.8 Summary

Atmospheric fogging in underground mines can be classified as very dense fog in meteorological terms. All mine fogs are warm fogs except for those experienced at Echo Bay Mines. Fog is caused by four main processes:

- (a) cooling of air to saturation temperature
- (b) addition of water and/or water vapour to the air
- (c) change in barometric pressure
- (d) mixing of moist air systems at different temperatures.

The presence of dust particles in the size range 0 to 10 μ m from mining operations ensures that there are always sufficient condensation nuclei for droplet formation at saturated conditions. The presence of large numbers of Aitken nuclei also assists in the development of fog. Diesel engine emissions can considerably increase the concentration of Aitken nuclei.

The visual range and visibility of a fog are inversely proportional to the liquid water content. It is probable that the Aitken nuclei concentrations result in smaller droplets which will reduce the visibility

according to the Trabert equation. This has not been proved and further investigation of the effects of the Aitken nuclei on visual range in fog is necessary to establish the extent of these effects.

Liquid water measurements of mine atmospheres indicate that concentrations up to 14.5 g/kg may be experienced with visibilities as low as 2 m. Canadian conditions are not as extreme as this and usually lie between 0.5 and 3.0 g/kg with visibilities from 73 m to 12 m. Fog can therefore present considerable problems in underground mining operations by reducing visibility.

3.0 SURVEY OF MINES WITH FOG PROBLEMS

3.1 Methodology

A telephone survey of mine inspectors and associated safety and health inspectors and organizations was conducted across Canada to determine which mines experience atmospheric fogging.

Individual mines were then contacted to determine the nature and extent of the problem which they were experiencing. Three mines were selected for personal visits to examine the effects of atmospheric fogging:

- (i) Mattabi Mines - Lyon Creek Mine, Ignace, Ontario
- (ii) Algoma Steel - G.W. MacLeod Mine, Wawa, Ontario
- (iii) Denison Mines - Elliot Lake, Ontario

3.2 Mine Visits

The three mines were visited during October, 1982; Mattabi on October 4th, Algoma on October 6th, and Denison on October 8th.

A considerable amount of information was obtained and the full details are set out in Appendix I. Fog was observed at all three mines during the visits and in summary the problems experienced are:

Mattabi

Impaired visibility on the Creek Zone service decline, which has resulted in closure to traffic in the past with consequent loss of production from this area. Under severe conditions, fog can exist in the stopes and ramps of the Creek Zone orebody. Liquid moisture contents of 1 g/kg are experienced in the circuit, which would require 500 kW of heat to prevent supersaturation of the present air flow of 85 m³/s at density 1.15 kg/m³. Fog occurs throughout the year but is particularly prevalent during June and July when the surface humidity is high.

Algoma Steel

Algoma experiences fogging in an essentially separate ventilation circuit which serves the cable belt and parallel service inclines. Fog reduces visibility in the service incline and hinders traffic. It is particularly prevalent during periods of high surface humidity, especially in early summer. Under severe conditions, the incline has to be closed to traffic despite deliberate short circuiting of air from the cable belt incline. White lines have been painted down both sides of the incline to assist visibility during foggy conditions.

The liquid moisture content of the air may exceed 2 g/kg of air and this results in visibilities of less than 15 m. Further problems are experienced with fog thickening in the vicinity of trucks, which are ascending the service incline.

Denison

Denison experiences fog to the east and northeast of the central exhaust corridor which handles almost 2,000 m³/s of air. The fog can be widespread under early summer conditions and it prevails throughout the year. The room and pillar mining method creates a large open area for the return air flow and it would be difficult to concentrate the flow for treatment to remove fog.

The fog causes closure of upper levels of the mine during severe conditions in early summer. The 22950 travelway is subject to fog throughout the year, which interferes with traffic.

Liquid moisture contents measured in October were 1.2 g/kg and it is apparent that this figure is exceeded during early summer. The October figure would correspond to a visibility of about 30 m which would affect operations.

3.3 Questionnaire

A questionnaire was developed and sent to 18 mines. Replies were received from 11 of these, representing a 60 per cent return.

Fog was reported by four companies:

- (1) Echo Bay - Lupin Operation, N.W.T.
- (2) Cominco - Con Mine, Yellowknife, N.W.T.
- (3) Canada Wide Mines Ltd. - Granduc Mine, Stewart, B.C.
- (4) Newfoundland Zinc Mines Ltd., Daniel's Harbour, Newfoundland

The questionnaire is set out in Appendix II of the report. In summary, none of these mines report severe fog problems.

Echo Bay experiences ice fog particularly during winter. The mine does not heat the air as it is in permafrost and surface temperatures of -20 to -50°C are experienced. Temperatures underground are of the order of -10°C. Pneumatic drilling produced localized fog and these drills have now been replaced with hydraulic equipment.

Con Mine reported fog in exhaust airways which are remote from working stopes and no major problems are experienced.

Granduc experience localized fogging which poses minor visibility problems. Localized fogging has resulted in water condensing on electrical gear and a ventilation change was undertaken to prevent this.

Newfoundland Zinc experience fog throughout the year with the least occurrence being in summer. The fog occurs in return airways and amber lights are used to outline narrow areas where visibility is reduced.

3.4 Occurrence of Fog

It is clear that several mines experience atmospheric fogging and that it can pose major problems when visibility is reduced. It is probable that fog is not limited to these mines but that other mines affected are either closed by the current economic conditions or did not reply to the questionnaire. Fog probably occurs in most mines to some extent but is accepted as an operational nuisance.

4.0 SYSTEMS FOR PREVENTING FOGGING

Fogging due to saturated or supersaturated air can be reduced or prevented by changing psychrometric conditions to reduce the humidity of the air.

This can be achieved by:

- (1) Heating of air
- (2) Raising air barometric pressure by compressing air
- (3) Addition of drier air to saturated air
- (4) Removing the moisture from the air by drying

These processes were evaluated to determine their energy efficiencies, relative to each other.

4.1 Heating of Air

4.1.1 Heating Air without the Addition of Moisture

The amount of heat required to reduce the relative humidity can be found from either the enthalpy or sigma heat of the mixture of air and water vapour, also known as vair.

Vair Enthalpy

This is defined as the sum of the enthalpy of air and the enthalpy of the water vapour. The water vapour enthalpy includes the sensible heat of water, latent heat of water vapour and superheat of water vapour for nonsaturated conditions.

The enthalpy of vair in kJ/kg of dry air can be determined from the relationship:

$$H = (1.005T_d) + [0.004187T_w + (2.501 - 0.002387T_w) + 0.001884(T_d - T_w)]ASH$$

where: H = enthalpy of air (kJ/kg)
 Td = air dry bulb temperature (°C)
 Tw = air wet bulb temperature (°C)
 ASH = apparent specific humidity (g/kg)

Sigma heat

Sigma heat is defined as the vair enthalpy minus the heat of the liquid and is determined from:

$$S = H - (0.004187Tw)ASH$$

$$\text{or } S = (1.005Td) + [(2.501 - 0.002387Tw) + 0.001884(Td - Tw)]ASH$$

where S is the sigma heat in kJ/kg of dry air.

4.1.2 Heating or cooling with moisture content change

Water at a temperature which may be significantly different from the air temperature can be introduced into or removed from atmospheric air. When a change in moisture content occurs, neither the enthalpy nor the sigma heat difference indicates the exact heating or cooling load, except under certain conditions or unless a correction is applied. The enthalpy difference provides the correct answer only if the water is introduced at 0°C, whilst the sigma heat difference gives the correct result only if the water is introduced at the air wet bulb temperature.

The correct heating or cooling load can be obtained from the sigma heat difference formulae:

(4-1)

$$\text{Heating load} = (S_2 - S_1) + 0.004187[(Tw_2 - Tin)ASH_2 - (Tw_1 - Tin)ASH_1] \text{ kJ/kg}$$

(4-2)

$$\text{Cooling heat} = (S_1 - S_2) + 0.004187[(Tw_1 - Tout)ASH_1 - (Tw_2 - Tout)ASH_2] \text{ kJ/kg}$$

where: T_{w1} = initial wet bulb temperature °C
 T_{w2} = final wet bulb temperature °C
 S_1 = initial sigma heat kJ/kg
 S_2 = final sigma heat kJ/kg
 $ASH1$ = initial apparent specific humidity g/kg
 $ASH2$ = final apparent specific humidity g/kg
 T_{in} = temperature of water absorbed by air °C
 T_{out} = temperature of condensed water °C

A detailed description of these psychrometric processes is given by Barenbrug (1974).

4.1.3 Effect of heating on saturated and supersaturated air

In order to evaluate the effects of heating, three different initial conditions for the air were considered. These three conditions were selected as being representative of fog conditions encountered on the mine visits and during early summer in Ontario.

These three conditions are:

- (1) Saturated air at 10.1°C, 97.5 kPa - barometric pressure, containing 8 g/kg of water vapour, sigma heat = 30 kJ/kg and density 1.193 kg/m³ - Case 1.
- (2) Supersaturated air at 10.1°C, 97.5 kPa - barometric pressure, containing 8 g/kg of water vapour and 1 g/kg of liquid water - Case 2.
- (3) Supersaturated air at 10.1°C, 97.5 kPa - barometric pressure, containing 8 g/kg of water vapour and 2 g/kg of liquid water - Case 3.

The effects of applying 5 and 10 kJ/kg of heat respectively were determined for each of the three conditions and are set out in Table 4-1.

TABLE 4-1

Effects of Applying 5 and 10 kJ of Heat Per Kilogram
of Air to 3 Saturated and Supersaturated Atmospheres

Condition Barometric Pressure (kPa) Case	Initial 97.5			5 kJ of Heating 97.5			10 kJ of Heating 97.5		
	1	2	3	1	2	3	1	2	3
Wet bulb temperature °C	10.1	10.1	10.1	12.2	12.20	12.20	14.1	14.10	14.10
Dry bulb temperature °C	10.1	10.1	10.1	15.1	12.70	12.20	20.0	17.60	15.20
Apparent specific humidity g/kg	8.0	8.0	8.0	8.0	9.00	9.20	8.0	9.00	10.00
Liquid water content g/kg	0.0	1.0	2.0	0.0	0.00	0.80	0.0	0.00	0.00
Total moisture content g/kg	8.0	9.0	10.0	8.0	9.00	10.00	8.0	9.00	10.00
Relative humidity %	100.0	100.0+	100.0+	72.2	94.80	100.00+	53.2	69.30	89.60
Sigma heat kJ/kg	30.0	30.0	30.0	35.0	35.00	35.00	40.0	40.00	40.00
Liquid water correction for Equation (1)	----	----	----	0.0	0.08	0.08	0.0	0.15	0.17
True heating applied kJ/kg	----	----	----	5.0	5.08	5.08	10.0	10.15	10.17

This shows the effects of heating the saturated and supersaturated air to evaporate the liquid moisture to vapour and thus reduce fogging. The calculations were performed using the psychrometric relationships given by Barenbrug (1974) and the computer program set out in Appendix III. All temperatures have been rounded to the nearest 0.1°C . The liquid water heating correction was calculated using Equation 4-1 and assuming that the liquid water was at the saturated air temperature for the supersaturated conditions, i.e. $T_{in} = T_{w1}$.

The application of the sigma heat correction results in approximately 1.5 per cent more heat being required than is indicated by the difference in sigma heats. The table indicates that 1 kJ/kg of heating under these conditions will result in 0.24 g/kg of extra water vapour capacity at saturation.

The latent heat of evaporation of water at a temperature of 10.1°C is approximately 2.48 kJ/g. Therefore, the evaporation of 0.24 g of liquid water should require 0.595 kJ of heat. The remaining heat is used to heat the air to the new equilibrium temperature and therefore heating vair to reduce fogging in these conditions results in 60 per cent of the heat being used for evaporation and 40 per cent being used to heat the air.

Heating the air component of the mixture is detrimental to fog prevention since it will result in increased heat transfer to the cold walls and sides of the airway. This can result in further fog formation further along the airway. If this component of the heating is considered waste and the heat used to evaporate the liquid moisture considered as useful work, then heating of vair under these conditions is 60 per cent efficient.

4.2 Raising Barometric Pressure by Compressing Air

The normal method of raising air pressure in mines is to pass the air through a fan. The effect of passing the air through a fan can be determined using the equations given by McPherson (1971).

$$\frac{dT}{dP} = \frac{0.286 (1+0.0016078ASH) T}{(1+0.0018235ASH) P}$$

for unsaturated air, and

$$\frac{dT}{dP} = \frac{0.287(1+0.0016078ASH)(P-E)T^3 + P \cdot L \cdot ASH \cdot T^2 / 1000}{5.106P[(P-E)(0.2396-0.5631ASH+TMC)T^2 + L \cdot ASH \cdot P(1334.6-T)]}$$

for supersaturated conditions,

where: $\frac{dT}{dP}$ = isentropic temperature rise per unit increase in pressure
°C/Pa

ASH = apparent specific humidity g/kg

P = barometric pressure Pa

E = saturated vapour pressure Pa

T = absolute temperature K

L = latent heat of evaporation of water kJ/kg
= [2501-2.387(T-273.15)]

TMC = total water content:- liquid and vapour g/kg

The same three initial conditions as for heating of air were assumed for evaluation of the effects of passing the air through a fan.

- (1) Saturated air at 10.1°C, 97.5 kPa - barometric pressure containing 8 g/kg of water vapour, specific heat = 30 kJ/kg and density 1.193 kg/m³.
- (2) As for (1) but supersaturated by 1 g/kg of liquid water.
- (3) As for (1) but supersaturated by 2 g/kg of liquid water.

Certain assumptions need to be made to evaluate the effect of the fan. The fan efficiency is assumed to be 70 per cent and the waste heat from the fan inefficiency is assumed to be added to the air. This would be the case for any fan where the motor is contained in the air stream.

The same amounts of work are assumed to be done on the vair as in the heating calculations, i.e. 5 and 10 kJ/kg respectively. Assuming a flow of 1 kg/s through the fan, then the inlet volume will be 0.838 m³/s. The total work input to the fan will be 5 and 10 kW, respectively. The fan pressures can now be found from the relationship

$$\text{Power Input} = \frac{PQ}{\eta} \text{ kw}$$

where: P = fan pressure rise kPa

Q = air quantity m³/s

η = fan efficiency

for the two cases

$$(a) \quad 5 = \frac{P \times 0.838}{0.7} \text{ and } P = 4.177 \text{ kPa}$$

$$(b) \quad 10 = \frac{P \times 0.838}{0.7} \text{ and } P = 8.353 \text{ kPa}$$

The initial and final conditions for the three cases are set out in Table 4-2. The table indicates that the effect of passing vair through a fan will result in approximately 0.22 g/kg of water being evaporated to vapour by each kJ/kg of work input.

The evaporation of this amount of liquid water should require approximately 0.55 kJ of heat. If a similar argument is used in the case of fans as in the case of heating, then the compression of vair

TABLE 4-2
Effect of Passing Saturated and Unsaturated Air Through Fans

Condition Barometric Pressure (kPa) Case	Inlet 97.5			Lower Pressure Fan Outlet 101.677			Higher Pressure Fan Outlet 105.853		
	1	2	3	1	2	3	1	2	3
Wet bulb temperature °C	10.1	10.1	10.1	12.6	12.6	12.7	14.8	14.9	14.90
Dry bulb temperature °C	10.1	10.1	10.1	15.0	12.7	12.7	19.6	17.4	15.20
Apparent specific humidity g/kg	8.0	8.0	8.0	8.0	9.0	9.1	8.0	9.0	10.00
Liquid water content g/kg	0.0	1.0	2.0	0.0	0.0	0.9	0.0	0.0	0.00
Total moisture content g/kg	8.0	9.0	10.0	8.0	9.0	10.0	8.0	9.0	10.00
Sigma heat kJ/kg	30.0	30.0	30.0	35.0	35.0	35.1	39.6	40.0	39.93
Relative humidity %	100.0	100.0+	100.0+	76.3	99.0	100.0+	59.4	76.6	97.10

under these conditions is 55 per cent efficient. Use of a fan is therefore comparable with air heating as a method of reducing the relative humidity of air.

4.3 Addition of Dry Air to Saturated Air

There are two sources of drier air that can be used to dilute saturated or supersaturated air:

- (a) lower humidity ventilation air
- (b) compressed air

The amount of power that is required for provision of extra ventilating air will depend on the availability of fresh air in the same area as the fogged air and the distance and manner in which it has to be moved to the mixing point. The psychrometric conditions of a mixture of two air streams of respective masses M_1 and M_2 kg is determined from the relationship:

$$\text{Apparent specific humidity of mixture} = \frac{M_1.ASH_1 + M_2.ASH_2}{M_1 + M_2} \text{ g/kg}$$

$$\text{Sigma heat} = \frac{M_1.S_1 + M_2.S_2}{M_1 + M_2} \text{ kJ/kg}$$

where

ASH1, ASH2, S_1 and S_2 are the apparent specific humidities and sigma heat contents of the individual streams, respectively.

Calculations have to be performed for local conditions to evaluate the efficiency of this alternative for the given circumstances.

The addition of compressed air to ventilating air is another method of reducing humidity. Compressors contain dryers and coolers so the

compressed air has low humidity. The power required to generate compressed air assuming an overall isothermal compressor efficiency of 64 per cent is 1 kWh/12.4 kg of free air compressed to 500 kPa gauge pressure. One kJ would produce 0.0034 kg of free air compressed to the same pressure.

Considering the same three cases, namely:

- (1) Saturated air at 10.1°C, 97.5 kPa - barometric pressure, containing 8 g/kg of water vapour, sigma heat = 30 kJ/kg and density 1.193 kg/m³ - Case 1.
- (2) Supersaturated air at 10.1°C, 97.5 kPa - barometric pressure, containing 8 g/kg of water vapour and 1 g/kg of liquid water - Case 2.
- (3) Supersaturated air at 10.1°C, 97.5 kPa - barometric pressure, containing 8 g/kg of water vapour and 2 g/kg of liquid water - Case 3.

If the same energy additions of 5 and 10 kJ/kg to the system are to be assumed, then the effects of adding 0.017 kg and 0.034 kg of such compressed air to 1 kg of atmospheric air must be evaluated. The apparent specific humidities and sigma heat levels of the mixtures have been calculated and are set out in Table 4-3, assuming that the compressed air has a pressure of 797.5 kPa and is at ambient temperature of 10.1°C. This corresponds to an apparent specific humidity of 1 g/kg.

It is readily seen that the addition of compressed air has a much smaller effect on humidity than the fan or heating for the same energy input. The effect is approximately 10 per cent of that of applying the energy as direct heat, since approximately 0.0024 g/kg of water are evaporated per kJ/kg of work input. This corresponds to an efficiency of approximately 6 per cent in use of the input energy. Release of compressed

TABLE 4-3

Effects of Mixing Compressed Air with Saturated
and Unsaturated Air at Barometric Pressure of 97.5 kPa

Condition Case	Initial			0.017 kg of Cold Air Added			0.034 kg of Cold Air Added		
	1	2	3	1	2	3	1	2	3
Wet bulb temperature °C	10.1	10.1	10.1	10.00	10.10	10.10	9.90	10.10	10.1
Dry bulb temperature °C	10.1	10.1	10.1	10.10	10.10	10.10	10.10	10.10	10.1
Water vapour content g/kg	8.0	8.0	8.0	7.88	8.00	9.00	7.77	8.00	8.0
Liquid water content g/kg	0.0	1.0	2.0	0.00	0.87	1.85	0.00	0.74	1.7
Total water content g/kg	8.0	9.0	10.0	7.88	8.87	9.85	7.77	8.74	9.7
Sigma heat kJ/kg	30.0	30.0	30.0	29.70	30.00	30.00	29.40	30.00	30.0
Relative humidity %	100.0	100.0+	100.0+	98.80	100.00+	100.00+	97.40	100.00+	100.0+

sed air results in expansion cooling of the compressed air. This causes local ventilation air cooling at the release point which can result in further fogging. The use of compressed air for dilution of fog is therefore not recommended.

4.4 Removal of Moisture from Air by Drying

Air drying systems commonly use the following methods:

- (a) heating
- (b) refrigeration/cooling
- (c) absorbtion
- (d) adsorbtion

(a) Heating

Heating has been discussed in the first section of this chapter and shown to have an evaporation efficiency of approximately 60 per cent.

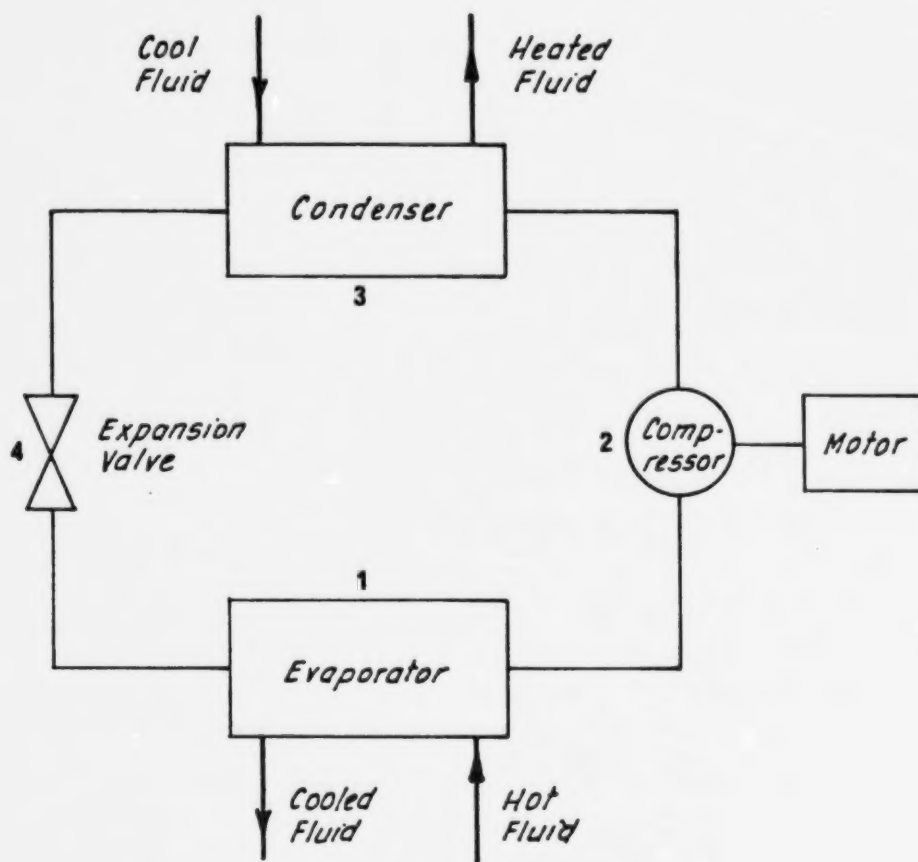
(b) Refrigeration

Refrigeration is often used because of the energy requirements of the system. A refrigeration machine has four components as shown in Figure 4-1: expansion valve, evaporator, compressor, and condenser. An efficient machine will use 1 kW of power input at the compressor to produce 3 kW of cooling at the evaporator and 4 kW of heating at the condenser. The use of low velocity air cooling coils on saturated air results in condensation of water on the cooling tubes and the condensate will run down to a collector from where it can be piped to a convenient drain or sump.

These installations are common in South African gold mines where individual coils of 250 kW capacity at air velocities up to 1 m/s are used to cool ventilation air in the deep workings.

VAPOUR COMPRESSION REFRIGERATION CYCLE

Figure 4-1



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The relative efficiency of a refrigeration machine acting as a cooler and reheater can be evaluated for comparison with direct heating or the use of a fan. The three cases considered will be the same as for the previous sections, namely:

- (1) Saturated air at 10.1°C, 97.5 kPa - barometric pressure, containing 8 g/kg of water vapour, sigma heat = 30 kJ/kg and density 1.193 kg/m³ - Case 1.
- (2) Supersaturated air at 10.1°C, 97.5 kPa - barometric pressure, containing 8 g/kg of water vapour and 1 g/kg of liquid water - Case 2.
- (3) Supersaturated air at 10.1°C, 97.5 kPa - barometric pressure, containing 8 g/kg of water vapour and 2 g/kg of liquid water - Case 3.

The system would be arranged as shown in Figure 4-2.

It is assumed that each kW of power input to the compressor will result in 2 kW of cooling at the evaporator and 3 kW of heating at the condensor, because of the temperature limitations of the system. The results are set out in Table 4-4. One kJ can remove 0.4 g of moisture. This corresponds to an evaporation efficiency of 99 per cent, because of the nature of the process.

It is readily seen that the cooler/reheater is an extremely efficient dryer if the condensate from the cooling coil is collected and removed from the air. The degree of drying achieved for a given work input is such that this method can have a considerably greater capital cost than a fan or heater but still have comparable overall costs.

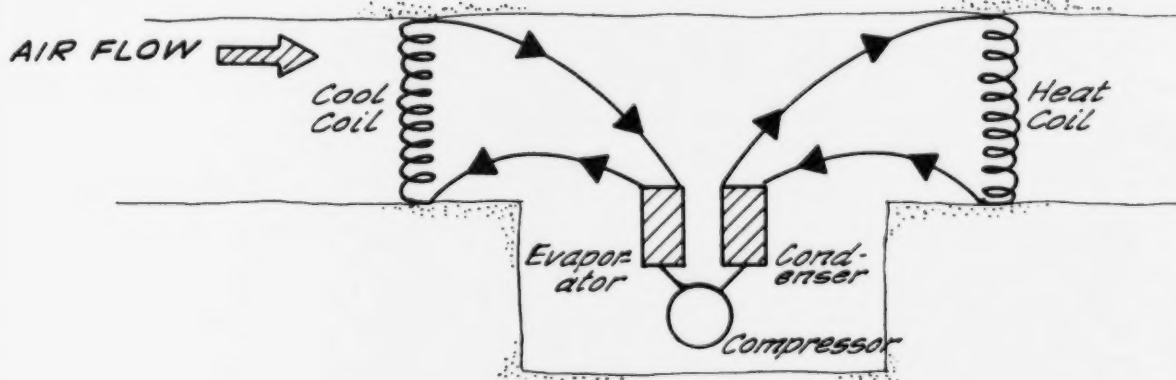
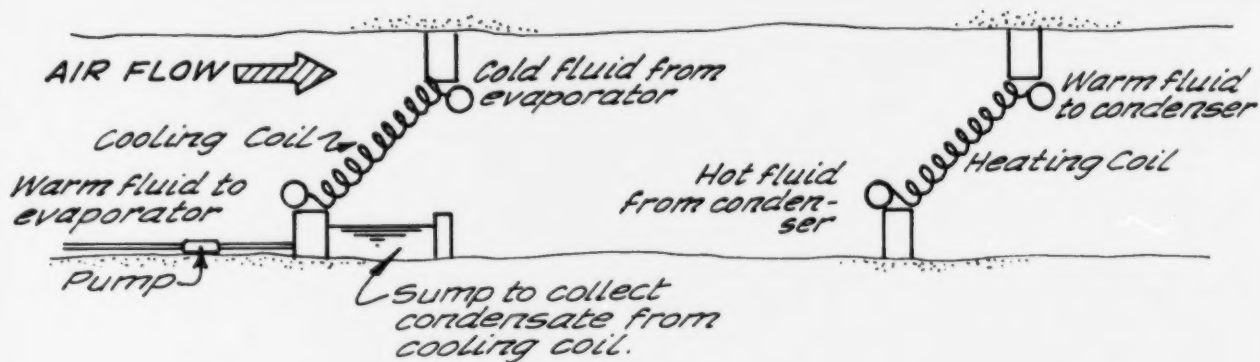
TABLE 4-4

Effects of Using a Refrigeration-Reheater
on Saturated Air at 97.5 kPa Barometric Pressure

Condition Case	Initial			5 kW Input		10 kW Input	
	1	2	3	All		All	
				Cooled	Reheated	Cooled	Reheated
Wet bulb temperature °C	10.1	10.1	10.1	5.5	12.2	0.1	14.1
Dry bulb temperature °C	10.1	10.1	10.1	5.5	20.5	0.1	29.8
Water vapour content g/kg	8.0	8.0	8.0	5.8	5.8	4.0	4.0
Liquid water content g/kg	0.0	1.0	2.0	0.0	0.0	0.0	0.0
Total moisture content g/kg	8.0	9.0	10.0	5.8	5.8	4.0	4.0
Sigma heat kJ/kg	30.0	30.0	30.0	20.0	35.0	10.0	40.0
Relative humidity %	100.0	100.0+	100.0+	100.0	37.3	100.0	14.8

TYPICAL REFRIGERATION MACHINE LAYOUT FOR AIR DRYING

Figure 4-2



Schematic only - Not to Scale

(c) Absorbition

Absorbition is a process of attracting one substance into the mass of another so that the absorbed substance disappears physically. Liquid and solid absorbents exist but for air drying it is common to use solid agents which react chemically with the water vapour in the air and liquefy. Such agents are often strongly corrosive and require regular replenishment.

(d) Adsorbition

Adsorbition is defined as the attraction and adhesion of gaseous and liquid molecules to the surface of a solid. Common adsorbents used in industrial drying are shown in Table 4-5 with their properties as given by Atlas Copco (1978).

Adsorbents can be regenerated by heating which drives off the water vapour so the adsorbent can be reused. It is seen from Table 4-5 that the most efficient adsorbent for regeneration is silica gel and that 1 kJ of heating will remove 0.12 to 0.14 g of moisture. This is approximately half the energy efficiency of heating or compression of the ventilating air. Adsorbents are not energy efficient but other factors may indicate their use in mine applications to prevent fogging.

4.5 Design of Ventilation System

The best method of preventing or minimizing fog formation is to design the mine ventilation system so that the opportunities for fog formation are reduced.

The primary consideration in design should be the provision of return airways which have minimum usage for man and material transportation and haulage. If fogging occurs in such airways, it will have a minimal effect on mining operations. The air velocity in these airways should be kept as high as possible to minimize the cooling effect of the airway walls, roof and floor on the ventilating air.

TABLE 4-5
Adsorbents used in Industrial Drying

Adsorbent	Approximate Dew Point °C	Maximum Temperature Air to be dried °C	Heat Consumption for Regeneration MJ/kg H ₂ O	Typical Regeneration Temperature °C	Surface Area m ² /g	Relative Cost \$
Raw silica gel	-50	+50	7.1 - 8.4	120 - 180	500 - 800	100
Spheroidal silica gel	-50	+50	7.1 - 8.4	120 - 180	200 - 300	170
Activated alumina W ₂ O ₃	-60	+40	9.6 - 11.3	175 - 315	230 - 360	150
Molecular sieves (NaWO ₂ .SiO ₂)	-90	+140	11.0 - 12.5	200 - 350	750 - 1100	550

In a mine with a ramp and shaft system, such as Mattabi, where a vertical raise exists parallel to the shaft, it would be preferable to use the ramp system for intake air and the vertical raise to exhaust air from the deeper levels.

The positioning of main fans in the circuit is very important as they play a major role in fog formation and prevention. If a fan is placed in the intake of a circuit and handles saturated air from the surface, then the effect of the fan will be to compress and heat the air as discussed in Section 4.2. This will result in the air having a greater capacity to hold moisture. The moisture content will increase as the ventilation air passes through the mine as shown by the humidities measured at Mattabi and Algoma Steel, see Appendix I. The cooling of this air and the decrease in pressure in the return airways results in atmospheric fogging. Positioning of the fans at the mine exhaust or in the return airway system would reduce the amount of water vapour in the air and reduce potential fogging. In mines where fogging is anticipated, it is recommended that the main fans should be installed on the exhaust side of the mine where ever possible.

The majority of the moisture contained in the air of the Canadian mines that were visited came from a saturated or very humid surface atmosphere. This reduces the potential benefits of decreasing the water usage in such mines. In all cases though, it is preferable to keep the air as dry as possible to reduce or prevent the incidence of fogging.

Three major methods can be used to achieve this:

- (i) drying out airways and covering drains;
- (ii) reduction of use of water sprays for dust control by replacing with filters;
- (iii) replacement of water scrubbers on diesel exhausts where possible.

(i) Drying our airways

Drying of airways is important to fog prevention. Poor drainage practice where water is allowed to accumulate on the foot-wall results in water being evaporated into unsaturated ventilation air. This reduces the air dry bulb temperature and the air capacity to hold moisture. Waste water should be contained in a drainage channel and such drains should be made to run in the return airways, where possible, to reduce the moisture pick up in the working sections of the mine. If fog occurs in such returns, then as long as there is no work required in these airways, it will not affect the mine production or safety.

Set mines with water flowing into the workings from underground fissures should arrange to collect and pipe as much water as possible to main drains or pump stations. This prevents the water from prolonged contact with the ventilating air and reduces moisture pick up.

Where drains flow through intake workings, they should be so arranged that either a pipe is used or else the drainage channel is covered to reduce the moisture pick up by the air.

Water reticulation systems should be checked for leaks and supply valves to stoping areas should be closed at blasting times to prevent any leaks due to blast damage of pipes.

(ii) Reduction of water sprays for dust control

Mines subject to atmospheric fogging should reduce their reliance on water sprays for dust control. Flannel bag filters can be used for dust control at dumps and crushers and spray usage is minimized. This results in reduced moisture pick up by the ventilating air. The use of atomizing sprays instead of ordinary sprays should be encouraged as the atomizing sprays pro-

vide better wetting of dust for suppression purposes and use less water. The use of filters rather than sprays at dumps also results in less water entering ore passes and reduces wet muck problems.

(iii) Use of catalytic scrubbers on diesel equipment

Water spray exhaust scrubbers on diesel-powered equipment are a large source of moisture added to the mine air. The replacement of water scrubbers with catalytic converters should be undertaken where possible. The relative applications and effects of such scrubbers have been documented by Mogan and Dainty (1980) and I.W. French (1978).

When atmospheric fogging occurs in mines despite the planning of the ventilation system and the reduction of water usage, it is necessary to use methods described earlier to reduce the nuisance.

4.6 Settling Out of Droplets

4.6.1 Vertical Airways

Water droplets in a vertical airway can either fall back against ascending airflow or be carried out at the top depending on the air velocity. Lambrechts (1956) investigated these effects and determined that there was an intermediate velocity at which the water droplets would remain suspended in the air and increase the shaft resistance. He recommended that design air velocities of 10 m/s should be avoided as such velocities allowed the droplets to accumulate. The velocity required to carry liquid out of the shaft would be 12.5 m/s and velocities less than 7.5 m/s will result in the water droplets falling back to the bottom of the airway.

In a vertical airway where water condensation may occur, the velocity can be designed to either carry the liquid water out of the top or

a low velocity can be used to permit the liquid water to fall down. Such water can then be collected in a sump at shaft bottom and piped away. This results in removing liquid water from supersaturated air and will reduce the incidence and severity of any atmospheric fogging which occurs between the settler and the mine exhaust point.

Air velocities between 7.5 and 12.5 m/s should always be avoided in the vertical airways of mines subject to fogging. The accumulation of water droplets which can build up at these velocities will not only create fog but will also considerably increase the airway resistance. Resistance and pressure loss values may approach twice the value for the same airway without water accumulation.

4.6.2 Horizontal Airways

Settling of water droplets in horizontal airways will obey Stokes Law:

$$V_s = \frac{d^2 g (WD - AD) 55.55 \times 10^{-12}}{AV}$$

where:

V_s = settling velocity mm/s

d = particle diameter μ m

g = 9.81 m/s² - gravitational acceleration

WD = water density kg/m³

AD = air density kg/m³

AV = air viscosity Ns/m² = 1814 x 10⁻⁸ at 21°C
1725 x 10⁻⁸ at 0°C

at 10°C

$$V_s = 3.08 \times 10^{-2} d^2$$

Table 4-6 shows the settling velocities of water droplets from 10 to 50 μ m in diameter.

Table 4-6
Settling Rate of Water Droplets in Air

Droplet Diameter μ m	Terminal Settling Velocity mm/s
10	3.08
20	12.32
30	27.73
40	49.29
50	77.02

Assuming an air velocity of 3 m/s in a 3 m high airway, then 50 μ m droplets forming at the roof will take 39 seconds to settle to the foot-wall in which time they will have been carried almost 120 m. The 10 μ m particles will take almost 1,000 seconds to settle and will have been carried 3,000 m. This indicates that settling of water droplets in a horizontal airway cannot be used to effectively remove moisture droplets less than 50 μ m in diameter from the air. These droplets will remain suspended and the fog will extend over a wide area.

4.7 Eliminators

Eliminators are commonly used in commercial air washers to remove liquid water from the airflow. Static eliminators consist of a series of vertical plates spaced from 25 to 50 mm on centres at the outlet side of the washer. The plates are usually 0.56 mm thick and are formed with a number of bends to deflect the air and obtain impingement on the wetted surfaces. Gutters are often provided on the edges of the eliminator

plates to improve moisture removal. High velocity air washers use rotating eliminators, consisting of a revolving assembly of sheet metal blades extending radially from a central hub (ASHRAE, 1972).

Since eliminators occupy the entire cross section of an airway, they cannot be used in any place where traffic passes, unless a by-pass ventilation airlock is constructed. The pressure drop across the eliminators will vary with the size and number of screens. Corrosion of the eliminators in return air may be a problem as blasting fumes can be extremely acidic in the presence of moisture.

Eliminators are therefore not recommended for use in the prevention of underground mine fogging and are unlikely to find application.

5.0 COSTS

5.1 Changing Psychrometric Conditions

The five usual methods of changing psychrometric conditions were described in the previous chapter and are ranked below in order of efficient energy usage:-

- (1) cooler/reheater
- (2) direct heating
- (3) fan compression
- (4) adsorbent drying
- (5) absorbent drying
- (6) air mixing with compressed air

The addition of dryer ventilation air to the fogged region can be used where practical and the efficiency of the process will be dependent on the local conditions. The unit costs of drying air using these methods have been estimated, together with specimen calculations for a typical mine. Present values were determined using lives of 5 and 10 years and 15 per cent per annum interest.

5.2 Cooler/Reheater

The use of a cooler/reheater will involve the purchase installation and maintenance of a refrigeration unit. The heat transfer process will remove 0.4 g/s of liquid moisture from air per kW of power input at the compressor of the machine under typical Ontario summer conditions. Since the latent heat of evaporation of water under these conditions is approximately 2.48 kJ/g, this corresponds to 0.992 kW of drying from the 1 kW power input. This is only possible because both the evaporator and condensor of the refrigeration machine are used in the drying process. Small refrigeration machinery has high capital cost and maintenance and the capital cost of a unit would be \$180 to \$200 per nominal refrigeration kW. The actual output of the machine may be only of the order of

65 to 70 per cent of the nominal capacity due to limitations placed on the machine by underground conditions. On the basis of figures given by Marks (1980), the annual maintenance costs would be \$60 and power costs \$60 per nominal refrigeration kW, based on a power cost of 2 cents/kWh.

Application of a system of this type requires the availability of adequate space for installation. If adequate space is not available, then it is necessary to provide a separate excavation which increases the installation cost considerably.

This system is particularly attractive when there is a large liquid water content in the air, provided the cooling coils fully precipitate the water. The costs of air drying are as follows:

(a) Saturated air

For 1 kW power input at compressor drying from air at 10.1°C

97.5 kPa = 0.4 g/s

actual refrigeration kW = 2.0

nominal refrigeration kW = $\frac{2.0}{0.67} = 3.0$

capital cost = 3 x 200 = \$600

Operating cost on 6 month operating basis for high humidity months = $\frac{3 \times (60 + 60)}{2} = \$180$

Capital cost of 1 g/s of moisture dried = $\frac{600}{0.4} = \$1,500$

Annual operating cost of 1 g/s of moisture dried g/s = $\frac{180}{0.4}$

= \$450

(b) Supersaturated air

If the air is supersaturated by 1 g/kg of liquid moisture, then 1.4 g/s of moisture will be dried by the cooler/reheater under the above conditions. The capital cost of moisture dried then becomes $600/1.4 = \$429/\text{g/s}$ and the annual operating cost = $180/1.4 = \$129/\text{g/s}$.

The cost decrease is even more marked if the supersaturation is 2 g/kg, then the capital cost falls to $\$250/\text{g/s}$ and the annual operating cost to $\$75/\text{g/s}$.

5.3 Direct Heating

The direct heating system requires the provision of suitable air heaters. Due to the dangers of propane, such heaters can only be installed on surface and are therefore of limited use in preventing fogging.

Electrical heaters are required for underground installation and three typical units supplied by Chromalox, Canada are described in Table 5-1.

The capital cost of drying 1 g/s of moisture is seen to be between \$44 and \$120 depending on the type of unit used and assuming that 1 kW of input power results in the evaporation of 0.24 g/s of moisture. The power cost for the units operating for 6 months will be \$88 and maintenance should be approximately \$10/kW per operating season. The annual operating cost therefore will be \$408/g/s of moisture dried. The size and simplicity of these units makes them readily applicable to underground areas where fogging occurs. The system is extremely flexible since the units can be operated as necessary to reduce fog. Excess capacity for average fogs can be shut-down to conserve power. The 60 kW capacity per unit provides an economic and flexible system, which is easily expanded or contracted according to need.

TABLE 5-1Electric Air Heaters

Type	BUH-604 Blower Unit Heat	DH48x28-100 Fintube Air Duct Heater	FDH36x37-65 Tubular Element Air Duct Heater
Capacity kW	60	100	65
Minimum air flow m ³ /s	1.0	2.4	2.2
Breadth (mm)	660	1,346	936
Height (mm)	510	813	924
Length (mm)	610	163	130
Cost (\$)	1,710	1,062	987
Capital cost/kW (\$)	28-50	10-62	15-18

5.4 Fans

The cost of a booster fan to handle $50 \text{ m}^3/\text{s}$ at a pressure of 2.5 kPa would approximate \$15,000 which is equivalent to \$120/kW of power input. This corresponds to a capital cost of drying of \$500/g/s, assuming 0.24 g/s of moisture are evaporated under the conditions set out in the previous chapter. The operating cost will be similar to that for direct heating, i.e. between \$400 and \$500/g/s of moisture dried.

Installation of booster fans has a higher capital cost than direct heating and may require the provision of an excavation for the fan which would add to the installation cost. Such installation would result in an increased airflow through the fogged section and the increased quantity will reduce the cooling effect of the rock and decrease fogging. Fans are inflexible in performance and are best suited for installations where the liquid water content of the air is constant over the fogging season.

5.5 Absorbents and Salts

The cost of silica gel is approximately \$5/kg, calcium chloride \$4/kg, and rock salt \$1.80/kg. Applications of at least 1 kg/m^2 will be required for drying so the capital cost of covering a large area will be considerable. During winter heating, the salt and absorbent may regenerate depending on the mine temperatures. A detailed calculation of cost can be done for individual situations to determine whether the method is economic for the given conditions.

5.6 Present Value of Alternative Systems

The present values of the three principal systems:

- (1) cooler/reheater
- (2) direct heating
- (3) fan compression

were determined for comparison purposes. The values were calculated for conditions similar to those existing in the return air ramp at Mattabi Mines - 85 m³/s of air flowing at a density of 1.15 kg/m³ at the measuring point.

The initial air condition was assumed to be 97.5 kPa barometric pressure and 10.1°C saturated, corresponding to a moisture vapour content of 8.0 g/kg. The supersaturation was assumed to be 0.5 g/kg of liquid water, which appears to be representative of average summer fog conditions.

The present values were calculated for equipment lives of 5 and 10 years to determine their sensitivity to changes in the life of the mine.

The present values of \$1/year at 15 per cent annual interest are:

<u>Year</u>	<u>Discount Factor</u>
1	\$ 0.8696
2	0.7561
3	0.6575
4	0.5718
<u>5</u>	<u>0.4972</u>
Present value of \$1/p.a for 5 yrs @ 15%	\$ 3.3522
6	\$ 0.4325
7	0.3759
8	0.3269
9	0.2843
<u>10</u>	<u>0.2472</u>
Present value of \$1/p.a for 10 yrs @ 15%	\$ 5.0188

5.6.1 Cooler/Reheater

The cooler/reheater was designed to cool the air to 7.8°C saturated, as this was considered to be the highest temperature which would still provide adequate heat exchange. The effect of the reheater would result in air outlet temperatures of 11.2°C W.B. and 15.4°C D.B.

	Wet Bulb (°C)	Dry Bulb (°C)	Relative Humidity (%)	Vapour Content (g/kg)	Liquid Content (g/kg)	Sigma Heat (kJ/kg)
Initial condition	10.1	10.1	100	8.0	0.5	30.0
After cooling	7.8	7.8	100	6.8	0	25.0
After reheating	11.2	15.4	61	6.8	0	32.5

Actual refrigeration required = $85 \times 1.15 \times (30-25) = 500 \text{ kW}$

Nominal refrigeration required = $\frac{\text{Actual refrigeration}}{0.67} = 750 \text{ kW}$

A 750 kW refrigeration machine would be standard and have a capital cost of $750 \times 200 = \$150,000$

The present value of the operating costs for a 5-year life = $750 \times 60 \times 3.3522 = \$150,849$

Present value of the operating costs for a 10-year life = $750 \times 60 \times 5.0188 = \$225,846$

Total present value - 5-year life = \$300,849
- 10-year life = \$375,846

5.6.2 Direct Heating

The installation was designed to use six BUH - 604 Heat Blower Units for heating the air.

	Wet Bulb (°C)	Dry Bulb (°C)	Relative Humidity (%)	Vapour Content (g/kg)	Liquid Content (g/kg)	Sigma Heat (kJ/kg)
Initial condition	10.1	10.1	100.0	8.0	0.5	30.0
After heating	11.7	12.6	90.3	8.5	0	33.7

Capital cost = $6 \times 1,710 = \$10,260$

Present values of the operating cost for a 5-year life = $360 \times 98 \times 3.3522 = \$118,266$

Total present value for 5-year life = \$128,526

Present value of the operating costs for a 10-year life = $360 \times 98 \times 5.0188 = \$177,063$

Total present values for 10-year life = \$187,323

5.6.3 Fan Compression

A fan with a pressure rise of 2.5 kPa is used for air drying. The efficiency of an underground fan is assumed to be 60 per cent.

	Pressure (kPa)	Wet Bulb (°C)	Dry Bulb (°C)	Relative Humidity (%)	Vapour Content (g/kg)	Liquid Content (g/kg)	Sigma Heat (kJ/kg)
Fan inlet	97.5	10.1	10.1	100.0	8.0	0.5	30.0
Fan outlet	100.0	11.9	12.6	92.4	8.5	0	33.7

Fan power input = $85 \times 1.15 (33.7 - 30) = 360 \text{ kW}$

Capital cost of fan = \$43,200

Present value of the operating costs for a 5-year life = $360 \times 96 - 3.3522 = \$115,852$

Present value of the operating costs for a 10-year life = $360 \times 96 \times 5.0118 = \$173,208$

Total present value - 5-year life = \$159,052

Total present value - 10-year life = \$216,408

TABLE 5-2
Comparison of Present Values

System	5-year life	10-year life
Cooler/reheater	\$ 300,849	\$ 375,846
Direct heating	\$ 128,526	\$ 187,323
Fan compression	\$ 159,052	\$ 216,408

5.7 Summary

The comparative present values of a typical application to Canadian fog conditions are shown in Table 5-2. It is readily seen that the direct heating of air will be the most attractive solution for mines with a fogging problem due to its extremely low capital cost. The small size and convenience of installation of these units together with their low maintenance requirements make them readily portable as mine workings develop. For these reasons, they are best suited to prevent or reduce underground fogging. They are also readily adaptable to changing liquid moisture contents by operating or stopping the 60 kW units as required.

Fans will be used as the second alternative because of their low maintenance requirements and the increase in air circulation which will result from their installation. This will increase velocities and reduce the cooling effect of the surrounding rock. Fans are best suited to applications where the liquid water content remains constant over the fogging season because fan performance is inflexible.

Cooler/reheaters will have limited application because of their complexity and high capital cost, but they should be considered for use in areas where the liquid moisture content consistently approaches 2 g/kg of air over a large period of the year. They are very efficient and result in greater drying for the same power input, but are subject to temperature limitations at small supersaturations which result in high power consumptions.

The other methods - settling, air mixing, adsorbents and use of compressed air can only be recommended when conditions prevent the use of the above three main methods, they will therefore find limited application.

6.0 RECOMMENDATIONS

6.1 Techniques

The previous chapters of this report have shown that the techniques available for fog control are:

- (1) Good ventilation planning
- (2) Direct air heating
- (3) Fan compression
- (4) Cooler/reheater
- (5) Adsorbent drying
- (6) Absorbent drying
- (7) Mixing of air with dryer air
- (8) Mixing of air with compressed air
- (9) Vertical airway water settling

The principal technique for elimination of fogging must always be good ventilation planning to prevent unnecessary contact between hot moist air and either cold air or rock. When a mine is planned using meteorological surface data and a reliable temperature prediction method, it is possible to minimize fog occurrence. Good planning will ensure dry airways, prevention of excessive water usage and a minimum of working places in return air.

In conditions where fog occurs, direct electric air heating is an economic solution because of its flexibility and ease of installation. The portability of the system makes it suitable for application in stope areas which change with production and ore grade requirements.

Fan compression will find application because it increases the air-flow quantity and decreases heat transfer. The system is inflexible because of the operating point of the fan and its major application will be at points of fixed liquid water content over the fog season as part of the overall mine ventilation plan.

Cooler/reheaters are attractive for application at points with high liquid water contents, approaching 2 g/kg and will have limited application in Canadian mines because such conditions are rare. The complexity and high capital cost of these units will discourage their use, except in mines with a known long life. The units are also difficult to relocate.

Chemical drying of air with common salt will find local application, especially where it is used to replace water spraying for dust suppression. Other chemical drying will have limited application due to cost and regeneration problems.

Air mixing with dryer air will be applied where it can be arranged economically as part of the overall ventilation layout for the mine. It will therefore form part of the ventilation planning process.

Air mixing with compressed air will be used as a last resort because of its extremely high cost.

Settling of water droplets in vertical airways will be used where it is possible to reduce the air velocity below 7.5 m/s to allow the droplets to fall to the bottom of the airways. Care must be taken to prevent velocities between 7.5 and 12 m/s in such airways which result in water cloud suspension with consequent high resistance.

6.2 Visibility

Every effort must be made to improve visibility in areas where fog occurs by increasing illumination without incurring glare. Reference markings, reflectors and amber coloured lights should be provided as necessary to improve visibility especially at areas with restricted clearance.

6.3 Safety

The imposition of safe speed limits and the provision of control traffic lights can be used in foggy areas to control speeds in accordance with the available visibility and prevent vehicles from entering the fogged area at the same time.

6.4 General Recommendations

6.4.1 Mine Design

Reliable meteorological data should be obtained for the surface air at the mine site for at least 12 months during mine planning. Frequently, this information is available from a local airport or weather station, with records covering several years. These records will indicate whether high humidity will occur and the months in which it is prevalent.

Temperature changes in the mine circuit can be calculated from heat transfer relationships, such as those developed by Starfield (1969). The main ventilation circuit can be analyzed and the risk of fogging can be determined.

An air circuit similar to Mattabi Mines is shown in Figure 6-1(a) and this system has several advantages for Canadian Mines. The intake air is heated in winter and travels down a vertical raise, leakage air upcasts through the vertical shaft and prevents it from freezing under winter conditions. The return air from the stopes ascends the access incline and the diesel exhaust fumes from the ramp are exhausted directly to surface.

Unfortunately, the system is best suited to a fan installation at the mine inlet and the cooling of the ascending air in the ramp creates fog conditions in summer.

An alternative layout for a similar mine is shown in Figure 6-1(b). In this system, the centre raise serves as a return airway and the fan can be mounted at either the mine inlet or at the top of the centre raise. The system reverses the flow in the access incline and any fog occurrence will be in the centre ventilation raise, where it will have no effect on mine operations. If the fan is positioned at the top of the centre raise, then any leakage flow into the vertical shaft will be downcast from surface. This may not be acceptable under winter conditions as it may result in freezing in the shaft.

When surface conditions such as lakes or muskeg prevent the provision of a central raise or where economics dictate a minimum of excavations, the fog problem can be reduced by reversing the ventilation flow as shown in Figure 6-1(c). The fan position in this design is critical.

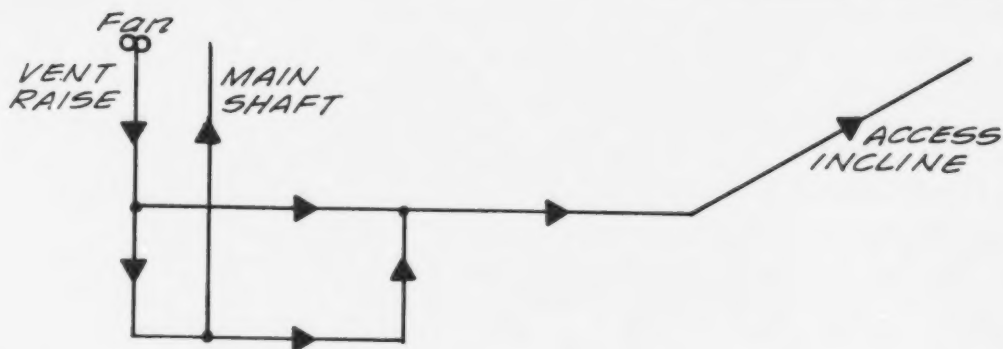
Positioning the fan at the surface intake of the access ramp results in a requirement for an airlock system at the top of the ramp and exhaust air which may be fogged flows up the main shaft. The intake air will also be heated by the fan. The fan should therefore be positioned at the top of the vertical raise and arranged to exhaust from the raise.

This arrangement creates minimal obstruction to the mining operation as the incline is an intake airway and does not require an airlock. The airflow will be downcast in the main shaft and this will prevent fogging. The arrangement will not be ideal under winter conditions as the mine heater will have to be placed at the entrance to the access incline and the leakage flow into the main shaft may cause freezing.

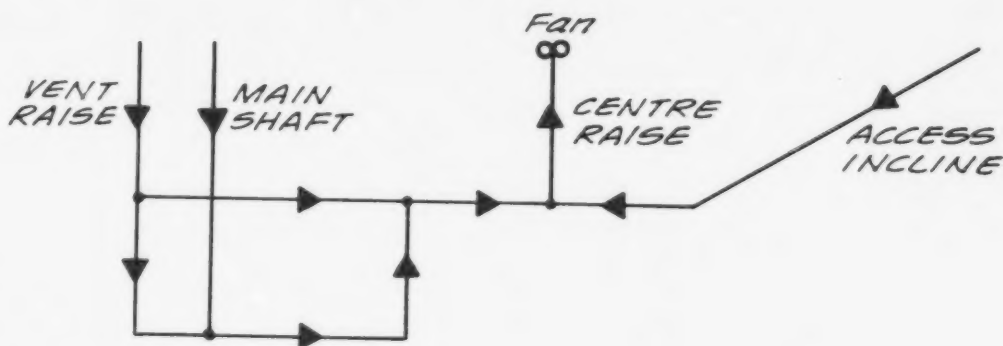
The optimum solution is to arrange the fan installation at the vertical raise so that the airflow can be reversed as shown in Figure 6-2. In winter whilst the heating is operational, the airflow will be as shown in Figure 6-1(a). Once the heating system is closed down, the

POTENTIAL AIR FLOW REVERSAL FOR MATTABI MINES.

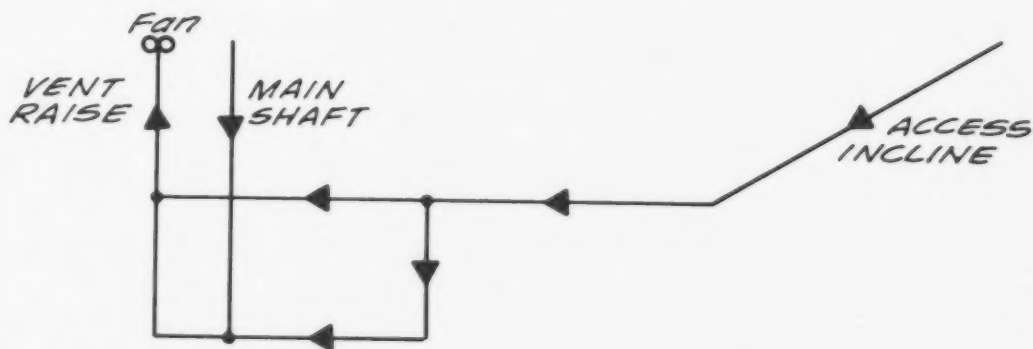
Figure 6-1



(a)



(b)

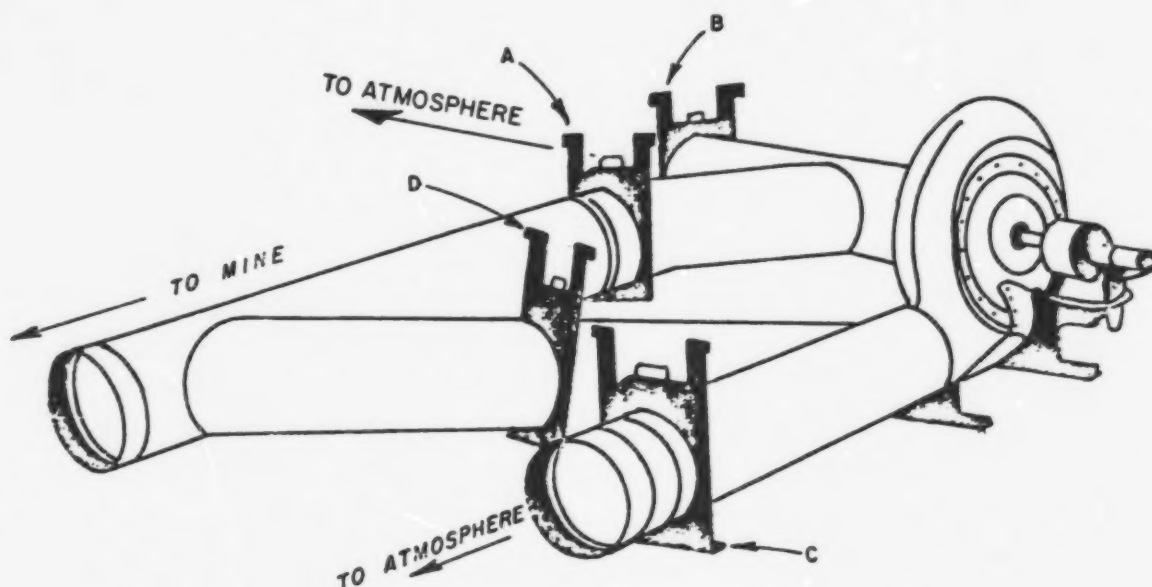


(c)

*"FOUR-GATE" SYSTEM FOR REVERSING
DIRECTION OF MINE AIR FLOW.*

Figure 6-2

*To force air into the mine - open gates B and D; close gates A & C.
To exhaust air from the mine - open gates A & C;
close gates B & D.*



Schematic only - Not to Scale

(after Weeks, p. 126)

airflow can be reversed for the summer fogging season as shown in Figure 6-1(c). This will result in the fog problem being minimized for the small extra capital expenditure to provide the fan flow reversal doors and removable section with replacement evasee.

Good mine design is the best method for preventing fog formation or reducing it to have minimal impact on the mine. The calculation of predicted temperatures at the mine planning stage and rearrangement of ventilation circuits as necessary to minimize fogging should be standard procedure for all fog prone mines.

6.4.2 Alleviation of Fogging in Existing Mines

Where fog occurs in an existing mine, the ventilation circuits should be examined to determine whether the fog can be prevented by redistributing the airflow. When this is not possible, the degree of supersaturation present in the fogged air should be determined from psychrometric charts or the computer program given in Appendix III. The required degree of drying can then be calculated and the present values of the alternative methods can be determined as shown in Chapter 5. The most economic method for the local conditions can then be selected. In most Canadian mines, where supersaturations will be of the order of 0.5 g/kg of liquid water, direct electric heating will likely be the selected method.

Mines which experience high supersaturations of 2.0 g/kg which exist for long periods will find that cooler/reheater systems are economically attractive.

The use of these systems should reduce the incidence of fog to minimal levels.

6.4.3 Techniques for Improving Visibility

The mine visits and questionnaires show that certain techniques are useful for improving visibility when fogging occurs. They should be used in local fogged areas where it is impossible or uneconomic to prevent fog formation. The most successful techniques are:

- (1) Painting of white reflective reference lines on the sidewalls of fogged areas.
- (2) Strategic use of fog lights to improve visibility.
- (3) Outlining areas with restricted height and/or width clearances with reflectors and amber lights.
- (4) Provision of traffic lights to prevent two vehicles entering a fogged zone at the same time.
- (5) Replacement of water scrubbers on diesel equipment by catalytic scrubbers.
- (6) Reduction in use of pneumatic drilling equipment by replacement with hydraulic drills.
- (7) Removal of water sprays at dumps and replacement with fabric filters.
- (8) Reduction in water usage, covering of drains, and the use of salt for footwall consolidation to prevent dust instead of watering down roadways.

6.5 Specific Recommendations

The following specific recommendations are made for the mines that were visited and the mines reporting underground fogging on questionnaires.

6.5.1 Matabi

Matabi should proceed with the trial heater installation and the effect on the occurrence and development of fog should be carefully

recorded to determine the optimum number of heaters to be installed to minimize fogging. The study of the psychrometric conditions in the mine indicates that this will be of the order of 500 kW of heating to completely eliminate fogging and about 360 kW under average conditions, relative positioning of the units should be altered and studied to determine the optimum spacing. It is recommended that a further project be initiated at Mattabi to observe the performance and effects of the heaters.

Consideration should be given to the possibility of reversing the mine airflow direction during the summer months as outlined earlier in this chapter to limit fogging to the vertical ventilation raise. The costs of the surface fan modifications and counterweighting of any ventilation doors should be compared with the heating costs. The most economic solution for the life of the mine can then be selected.

It is recommended that reflective paint stripes should be installed on the sidewalls of the decline, if fogging persists and that reflectors and amber lights should be installed to indicate the outline of unusually restricted sections of the decline.

6.5.2 Algoma

The ventilation system in the vicinity of the two inclines should be reviewed to determine whether it is possible to divert other air from the rest of the mine into the circuit to reduce the humidity. In the event that this is not possible, consideration should be given to repositioning the fan in the circuit. The position of the fan at the intake results in saturated surface air being reduced to below 100 per cent relative humidity. The air pressure increases as it descends the cable belt incline and moisture is picked up in the mine. The possibility of using the fan as an exhaust fan should be investigated and a test arranged if this can be done at low cost.

The water usage in the two inclines should be examined and efforts be made to reduce this to a minimum consistent with satisfactory dust control. The use of calcium and sodium chloride salts, which act as absorbents, for consolidating footwalls and controlling dust has been described by Goddard et al (1974). A salt application should be tested to consolidate the incline footwall. It would be preferable to use this system if the cable belt incline could be used as the return, since the consolidated footwall would not be subjected to vehicular traffic.

Common rock salt in granular form can be used and spread manually if used in the conveyor incline. An application in the service incline could be spread mechanically using a similar method to that used for salting highways in winter.

When the atmospheric humidity is less than 75 per cent, the air will take water from the salt producing, in turn, crystallisation. In humidities greater than 75 per cent, the salt will extract moisture from the air and assist in air drying. Sodium chloride is effective for two to four months. Heating of the incline by the passage of diesel equipment will help regenerate the salt.

Calcium chloride is not recommended because of its higher cost and corrosive effect on metals.

The installation of direct heating in the service incline should be considered if neither of the above measures is possible or successful. The amount of heating required is likely to be of the order of 500 kW which should be arranged at regular spacings in the upper part of the service incline. The effects of such heaters should be carefully observed and the spacings should be adjusted using the results of the observations until the optimum arrangement is achieved.

Restricted sections of the incline should be outlined by reflectors and amber lights to improve visibility if fog persists after the heating is installed.

The use of pilot red and green lights to control traffic in the incline and the provision of repeater lights in the upper section should be investigated to provide reassurance for drivers.

6.5.3 Denison

The fog problem at Denison is severe because of its extent and the extremely large air volume passing through the exhaust corridor. It is not possible to heat this volume and the mine layout on the room and pillar system prevents the collection of air so that it can be passed on through a fan or fan system. This would also affect the overall mine system.

Reversal of the mine airflow direction at Denison is not practicable because of the large quantities and the numerous ventilation doors and controls which would require modification to handle the flow reversal.

The problem can be reduced by minimizing the amount of work done in the fogged areas during summer but this may provide scheduling problems as well as affecting grade control.

Two trial solutions are proposed for consideration by the mine:

- (i) the use of local portable heaters and fans to improve velocities and reduce fogging in sections which require to be worked;
- (ii) the testing of a salt floor covering in the fogged area to determine its effect on fogging.

Local portable electric heaters and fans can be applied to stoping operations in the fogged area. These will clear the air in the working face by increasing velocities and temperatures, with consequent reduction of relative humidity.

Blower unit heaters are available with capacity from 2 to 60 kW and fintube air duct heaters from 1 to 100 kW as standard units with 4 to 6 weeks' delivery. Units of this type should be tested in the fogged area to determine the optimum arrangement for Denison's conditions.

Salt application to the footwall of a fogged area should be tested to determine its effect and life on a part of the haulage road. If the application is successful, larger areas of the mine can be treated to reduce the air humidity.

6.5.4 Echo Bay Mines - Lupin Operations

It is understood that the mine has replaced pneumatic drilling by hydraulic equipment. This will prevent the fogging due to moisture vapour in the compressed air. The water traps and driers of the compressed air system should be regularly checked to ensure the maximum moisture removal, as long as pneumatic equipment continues to be used.

Consideration should be given to fog occurrence in the future planning of the ventilation layouts to minimize the mixing of warm humid air streams with cooler air.

6.5.5 Granduc Mines

The scrubbing systems available for the Volvo DM trucks should be investigated to try to develop a dry system which can be used to replace the present water scrubbers.

Local air heating should be considered in areas experiencing fogging which severely restricts visibility or results in condensation on electrical equipment.

The application of paint lines and reflectors should be examined to determine whether they will assist in improving visibility at localized fog areas, especially with reduced clearance.

6.5.6 Newfoundland Zinc

Consideration should be given to installation of electric heaters at any area which is causing concern, especially at the narrow areas outlined by amber lights. The heaters should be investigated to determine the optimum number and spacing for the prevailing conditions.

The general recommendations for improving visibility should be reviewed to determine their application to the mine conditions.

6.5.7 Con Mine

Fog occurrence is limited to areas where no work is taking place. In the event that work is necessary in these areas, the purchase of blower heaters can be considered and the general recommendations for improving visibility can be reviewed to determine their applications.

7.0 RECOMMENDATIONS FOR FUTURE WORK

The study has highlighted a number of areas which would benefit from further research and investigation.

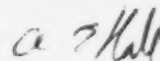
- A standard visibility determination method should be established and used by all mines experiencing fog. The standard could be used for comparative purposes and to determine the relationship between visibility and liquid water content of the air.
- The heater installation of Mattabi should be used as a test site to evaluate the heater performance and effectiveness. Careful psychrometric readings should be obtained to determine liquid moisture content values for extreme and average conditions. The effects of varying the relative spacing of the heaters and the degree required to prevent fog recurrence should be determined. This would be a suitable project for a post-graduate student at a Canadian university.
- The development of an optimized local direct heating drying system suitable for use at Denison Mines should be initiated. This project could be combined with research into the effects of footwall salt treatments and a parallel investigation could be conducted into the effects of liquid moisture contents on underground visibility.
- Diesel exhausts should be examined to determine whether the number of Aitken nuclei released have an effect on the onset of condensation. The investigation should determine the relative humidity at which condensation begins in a mine with large amounts of diesel equipment. The effect of alternative scrubber systems on fog formation should be quantified and recommendations made for the development of dry systems suitable for use on all engines.

- A lighting study should be initiated to determine the optimum means of illumination and the best reference reflectors and markings for use in improving visibility in fogged areas. MAPAO would be a suitable body to conduct the investigation.
- A central register should be established for all mines experiencing underground fog. This should be reported through the Provincial Mine Inspectorates so that experiences and procedures can be communicated to other mines to assist them in solving this problem.

Yours very truly,



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APPENDIX I

Mine Visits

MINE VISITS

Selection of Mines

A telephone survey of the following organizations was conducted to locate Canadian mines having atmospheric fogging problems:

Alberta

Workers Health, Safety and Compensation, Edmonton
Energy and Natural Resources, Edmonton

Saskatchewan

Mineral Resources, Mines Branch, Regina
Labour Department, Mines Inspectorate, Regina

Manitoba

Mining Inspectorate, Winnipeg

Ontario

Mining and Petroleum Resources, Toronto
Ministry of Labour - Industrial Health and Safety Inspectorate,
Toronto
Mine Accident Prevention Association of Ontario, North Bay

Quebec

Department of Natural Resources, Quebec City
Quebec Metal Mining Association

Nova Scotia

Department of Mines, Halifax
Workers Compensation Board, Halifax

New Brunswick

Department of Natural Resources - Mines Division, Fredericton

British Columbia

Ministry of Energy, Mines and Petroleum Resources, Mines Inspectorate, Vancouver

Several mines were then contacted individually and three mines were selected for personal visits to examine the nature and magnitude of their problems:

- (1) Mattabi Mines - Lyon Creek Mine, Ignace, Ontario
- (2) Algoma Steel - G.W. MacLeod Mine, Wawa, Ontario
- (3) Denison Mines - Elliot Lake, Ontario

The mines were visited during October, 1982; Mattabi on October 4th, Algoma on October 6th, and Denison on October 8th. Production figures were obtained from the Canadian Mines Handbook, 1982 edition, for inclusion in this section.

Mattabi Mines

Mattabi is a zinc-copper-silver and lead producer situated in the Sturgeon Lake area of Ontario about 60 km north of Ignace. The 1981 production figures were 521,000 tons milled to produce 845 tons of copper, 26,960 tons zinc, 1,020 tons lead and 753,000 ozs of silver.

An air volume of $85 \text{ m}^3/\text{s}$ (180,000 c.f.m.) is circulated through the main mine workings by 2 Joy vane axial fans of 1,372 mm (54 inches) diameter situated at the intake to the ventilation raise and having a static pressure of 2.24 kPa (9 in.w.g.), see Figure I-1.

The air enters the mine through the Lyon Lake ventilation raise and is first used to ventilate the Lyon Lake orebody. The air exhausts to the 600 level where $71 \text{ m}^3/\text{s}$ (150,000 c.f.m.) are transferred to the bottom of the Creek Zone decline. The remaining $14 \text{ m}^3/\text{s}$ (30,000 c.f.m.) returns along the 200 level past the surface fill raise and mixes with the $71 \text{ m}^3/\text{s}$ at the top of the Creek Zone decline. All the air is then exhausted through the service incline to surface.

TABLE I-1
Temperature Readings - Mattabi Mines

Station	Surface		31		33		37		34		200-Surface		Fog Extent
	W.B.	D.B.	W.B.	D.B.	W.B.	D.B.	W.B.	D.B.	W.B.	D.B.	W.B.	D.B.	
Date 1981													
June 1st	14.0	21.00	9.20	9.20	9.00	9.00	9.50	9.50	12.00	12.50	----	----	525 Ramp to Portal
16th	7.0	8.75	9.50	9.50	10.00	10.00	10.00	10.00	10.00	10.00	----	----	525 Ramp to Portal
18th	11.0	12.00	10.00	10.00	10.25	10.25	10.75	10.75	9.00	9.00	----	----	600 to Portal
22nd	11.5	15.50	10.20	10.50	10.50	10.70	11.20	11.50	9.00	9.00	10.5	10.7	200 Level
23rd	11.5	15.50	10.50	11.25	11.50	12.00	10.75	11.50	9.75	9.75	----	----	200 Level
24th	12.0	12.50	11.00	11.00	12.00	12.50	11.50	11.70	8.50	8.50	10.5	11.5	200 to Portal
25th	11.5	16.50	10.70	11.00	11.20	11.50	11.00	11.50	8.20	8.20	10.2	12.5	200 + Decline
26th	14.0	17.00	10.50	10.50	11.50	11.50	11.20	11.50	9.50	9.50	11.5	13.0	200 to Portal
29th	14.0	14.50	12.00	12.00	12.20	12.50	11.70	12.00	11.70	11.70	14.0	14.5	Portal
30th	16.0	17.50	11.25	11.75	11.50	11.75	11.25	11.75	10.50	10.50	----	----	200
July 1st	14.0	19.20	11.70	11.70	11.50	12.50	11.50	12.00	10.00	10.00	12.0	14.0	Portal to 200
Assumed Barometric Pressure (kPa)	95.6		95.9		96.2		96.4		96.2		96.2		

Note: W.B./D.B. - Wet Bulb/Dry Bulb measured in °C

In 1981, Mattabi lost 10 days of production in the Creek zone due to fog impairing visibility. During this period, observations were taken at the underground stations shown in Figure I-1. Unfortunately, barometric pressures were not taken and the assumption has been made that the surface barometric pressures 440 m (1,446 ft.) above sea level was 95.6 kPa and that the pressure increased by 1 kPa for every 100 m of depth below surface. The fan pressure was excluded as a variation of 2.5 kPa in barometric pressure would only change moisture contents by 0.1 g/kg and have approximately 2 per cent effect on enthalpies. These differences are negligible because the assumed barometric pressure may be in error by a similar amount.

The results are set out in Table I-1 and the calculated water vapour content and enthalpies are set out in Table I-2. The water vapour content change and total heat loss for a flow of $85 \text{ m}^3/\text{s}$ at a density of 1.15 kg/m^3 , which corresponds to surface conditions, are also shown.

A temperature survey of the mine had been conducted on October 1st, 1982 using the stations shown in Figure I-1. The results are set out in Table I-3.

It is seen that the water vapour content of the air is a maximum at Station 3 between 525 and 600 levels and that the water vapour content at Station 31 is 0.7 g/kg less than this. The difference will appear in the air as liquid water droplets and if the Koschmieder and Chylek equations apply, then the visibility would be 43.7 m.

It is significant that the two severest fogs of 1981 occurred when the saturated air at Station 31 had a maximum water vapour content of less than 8.0 g/kg. This indicates that the mine air normally achieves a moisture content exceeding 8 g/kg in the Lyon Lake zone and due to cooling of air by the rock temperatures of 6°C and less, liquid water condenses out in droplet form in the Creek Zone or in the service

TABLE I-2
Moisture Contents and Enthalpies - Mattabi Mines

Station	Surface		31		33		37		34		200-Surface Raise		Water Vapour Content Change Stn 37 to 31 g/kg	Heat Loss Surface to Surface to Stn 31 kW
	W.V.	E.	W.V.	E.	W.V.	E.	W.V.	E.	W.V.	E.	W.V.	E.		
Date 1981	W.V.	E.	W.V.	E.	W.V.	E.	W.V.	E.	W.V.	E.	W.V.	E.		
June 1st	7.7	40.6	7.6	28.5	7.5	27.9	7.8	29.1	9.0	35.3	---	---	-0.2	1186
16th	5.9	23.6	7.8	29.2	8.0	30.3	8.0	30.3	8.0	30.3	---	---	-0.2	(-548) Gain
18th	8.2	32.9	8.1	30.4	8.2	30.9	8.4	32.1	7.5	27.9	---	---	-0.3	245
22nd	7.3	34.0	8.1	30.8	8.2	31.5	8.6	33.2	7.5	27.9	8.2	31.5	-0.5	314
23rd	7.3	34.0	8.0	31.6	8.7	34.0	8.1	32.1	7.9	29.7	---	---	-0.1	235
24th	9.0	35.4	8.6	32.8	9.0	35.2	8.8	34.0	7.3	26.8	7.9	31.5	-0.2	255
25th	6.9	34.0	8.3	32.1	8.6	33.2	8.4	32.7	7.1	26.1	7.3	30.7	-0.1	186
26th	9.3	40.7	8.3	31.6	8.9	34.0	8.6	33.2	7.8	29.1	8.3	34.0	-0.3	899
29th	10.4	40.8	9.2	35.3	9.2	35.8	8.9	34.4	9.0	34.5	10.3	40.6	+0.3	539
30th	11.4	46.5	8.6	33.4	8.8	34.0	8.5	33.3	8.3	31.5	---	---	+0.1	1284
July 1st	8.4	40.6	9.0	34.6	8.5	34.0	8.7	33.9	8.0	30.3	8.4	35.2	+0.3	508

Note: W.V. - Water Vapour content measured in g/kg
E. - Enthalpy measured in J/kg

TABLE I-3Temperature Survey - Matabi Mines - October 1st, 1982

Station	Estimated Barometric Pressure kPa	Wet Bulb Air Temperature (°C)	Dry Bulb Air Temperature (°C)	Water Vapour Content (g/kg)	Enthalpy (J/kg)
Surface	95.6	4.8	5.0	5.6	19.0
1	97.4	8.5	10.5	6.3	26.5
2	97.4	9.5	11.0	7.1	28.8
3	97.3	11.0	11.0	8.5	32.5
4	97.4	10.5	10.5	8.2	31.2
5	97.2	10.8	11.0	8.3	32.0
31	95.9	9.5	9.5	7.8	29.2
33	96.2	9.6	9.6	7.8	29.3
34	96.2	9.2	9.2	7.6	28.4
37	96.2	10.5	10.5	8.3	31.5

decline. The temperatures and enthalpies of air required to increase the water vapour content were calculated together with the total kW required to heat $85 \text{ m}^3/\text{s}$ of air and are set out in Table I-4.

TABLE I-4

Heat Required to Increase Water Vapour
Content at Mattabi Station 31
(Barometric pressure = 95.9 kPa)

Saturated Temperature (°C)	Saturated Water Vapour Content (g/kg)	Enthalpy J/kg	KiloWatts of Heat to Increase Temperature from 9°C Saturated for an Airflow of $85 \text{ m}^3/\text{s}$ at a density of $1.15 \text{ kg}/\text{m}^3$
9	7.5	28.0	---
10	8.1	30.4	235
11	8.6	32.8	470
12	9.2	35.3	715

These values indicate the amount of heating that would be required to raise the air temperatures to remove the liquid water content at a barometric pressure of 95.9 kPa. The amount of heat required is considerable and almost 500 kW would be required to evaporate a liquid moisture content of 1 g/kg.

Conditions in the incline and at the portal are shown in Photographs 1 to 4. The photographs show the effect of the fog on visibility in the incline and the fog emission at the portal. The failure of the truck lights to effectively penetrate the fog is seen in Photographs 2 and 3. Such impairment of visibility is clearly hazardous and reduces speeds and hence the production rate of the ore trucks operating in the incline and Creek Zone. There is no doubt that the atmospheric fogging at Mattabi creates a severe problem in operating the Creek Zone.

Algoma Ore Division, Wawa

The George W. MacLeod Mine is situated at Wawa, Ontario, and mines siderite ore which is sintered at the mine. The production in 1981 was 1,461,733 gross tons from a mine production of approximately 2,500,000 tons. Production since August 1979 has come from the Stage 4 development and ore is transported to surface by a single lift cable belt conveyor, approximately 4.8 km long.

The fog problem occurs in an essentially separate ventilation circuit which serves the cable belt and parallel service inclines. A plan of the inclines is shown in Figure I-2. The airflow pattern is shown on Figure I-2. An air quantity of $60 \text{ m}^3/\text{s}$ (126,000 c.f.m.) is circulated by the fan at the entrance to the cable belt incline. The majority of the air leaks through the doors at the 21 crosscut connections and returns through the service incline. The psychrometric properties are set out in Table I-5.

The table indicates that the liquid moisture content of the air may exceed 2 g/kg. Barometric pressures were estimated using a value of 99 kPa for the surface pressure and increasing the pressure by 1 kPa/100 m of depth below surface.

Conditions in the service incline are shown in Photographs 5 and 6. Algoma use a white painted strip on the sidewalls and reflectors to improve visibility. It is apparent from the photographs that swirling mist severely hampers visibility and that the visual range is less than the 18.3 m predicted by the Koschmieder and Chylek equations.

The incline is used by trucks and material transporters servicing the large diesel service shop on M5 level. It was reported that during early summer surface humidity conditions, visibility may deteriorate to such an extent that it is impossible to drive through the incline despite short circuiting air from the cable belt tunnel to the service incline. Conditions are usually clear below No. 18 crosscut, where unsaturated air from another mine circuit is mixed in.

TABLE I-5

Psychrometric Conditions in Cable Belt and
Service Inclines at Algoma Steel, Wawa, October 6th, 1982

Station	Estimated Barometric Pressure (kPa)	Wet Bulb (°C)	Dry Bulb (°C)	Moisture Content (g/kg)	Enthalpy (J/kg)	Remarks
Surface	99.0	10.0	10.0	7.8	29.7	Raining
Portal exhaust	99.0	9.5	9.5	7.5	28.6	Clear
4X/C Service	100.3	11.0	11.0	8.2	31.8	Slight fog
4X/C Cable	100.3	9.0	10.0	6.8	27.1	Clear
6X/C Service	101.0	11.3	11.3	8.4	32.4	Slight fog
11X/C Service	102.7	12.5	12.5	8.9	35.0	Clear
11X/C Cable	102.7	11.8	12.5	8.2	33.3	Sight fog
15X/C Service	104.0	13.8	13.8	9.6	38.0	Slight to no fog
15X/C Cable	104.0	13.0	13.7	8.8	36.0	Clear
17X/C Service	104.7	14.1	14.5	9.5	38.7	Clear
18X/C Service	105.0	14.3	14.9	9.6	39.1	Clear
20X/C Service	105.7	14.2	15.8	9.0	38.7	Clear
20X/C Cable	105.7	14.2	14.5	9.5	38.7	Clear
21X/C Cable	106.0	14.2	15.0	9.3	38.6	Clear
23X/C Cable	106.7	15.2	16.0	9.9	41.1	Clear
23X/C Service	106.7	14.8	15.5	9.7	40.0	Clear

The increase in moisture content through the mine circuits is small but there is considerable cooling of the return air in the service incline due to heat transfer into the rock. This is the principal cause of the atmospheric fogging. Table I-6 sets out the moisture contents and enthalpies for saturated air at different temperatures with a barometric pressure at 99 kPa and the heat required to increase the water vapour content of the 40 m³/s of return air.

TABLE I-6

Heat Required to Increase Water Vapour
Content at Algoma Service Decline
(Barometric pressure = 99 kPa)
(Air density = 1.22 kg/m³)

Saturated Temperature (°C)	Saturated Water Vapour Content g/kg	Enthalpy kJ/kg	KiloWatts of Heat to Increase Temperature from 9.5°C Saturated for an Airflow of 40 m ³ /s
9.5	7.5	28.6	---
10.0	7.8	29.7	54
11.0	8.4	32.1	171
12.0	8.9	34.1	268
13.0	9.6	37.2	420
14.0	10.2	39.8	547

The amount of heating required to heat the air above saturation is considerable.

The incline is used daily by an explosive truck and by service trucks supplying materials to the main diesel shop. The 20-ton Jarco trucks are reported to affect fog conditions. The trucks appear to travel through the incline at approximately the same speed as the ventilation air. The waste heat from the engine and exhaust clear the fog in the immediate area of the truck but it is reported that the truck appears to push fog in front of itself, when ascending the incline. This creates a denser fog in front of the truck and reduces visibility for descending traffic.

The re-establishment of fog after the truck has passed produces a swirling effect and it is reported that visibility is reduced below the average value for the incline with no traffic. This is subjective and it may be that this is a psychological effect rather than a true physical thickening of the fog.

The fogging at Algoma creates problems and it would be desirable to prevent its occurrence.

Denison Mines, Elliot Lake

Denison Mines is a uranium producer at Elliot Lake, Ontario. The production in 1981 was 4,743,000 lbs of U_3O_8 from 3,074,000 tons milled. Mechanized room and pillar mining is the principal mining method.

Denison and its ventilation system have been described by Stenning (1978). The main ore zone varies from 1.8 to 10 m in thickness and has an average dip of 19 degrees. Design criteria must consider a largely mechanised operation and a radioactive and highly siliceous ore.

Forty-eight types of diesel equipment are used in the mine. The recent ventilation expansion program has increased the volume circulated to more than $2,400 \text{ m}^3/\text{s}$ (5,000,000 c.f.m.). This large airflow is expensive, Chakravatti (1980) reported a ventilation cost of $\$1,500/\text{m}^3/\text{s}/\text{year}$. Any confinement of the air to airways instead of allowing it to flow through the rooms and pillars would increase the velocities, resistance, and power costs considerably.

The fog problem occurs to the east and northeast of the central exhaust corridor which returns $1,085 \text{ m}^3/\text{s}$ (2,300,000 c.f.m.) to the 15 panel exhaust raise and $897 \text{ m}^3/\text{s}$ (1,900,000 c.f.m.) to the Knowles Island exhaust raise. The return air is cooled as it passes through the workings and condensation of liquid water occurs causing fogging. The fog is widespread at times as shown in Figure I-3 and creates visibility problems along the 22950 travelway.

The existence of the fog over this area of approximately 1,000 m wide by 700 m long prevents working in the area under severe conditions and reduces production when visibility is reduced. The control of flows is complex and numerous stoppings and a substantial number of doors have been erected to provide positive control to the different sections (Stenning, 1978).

It is apparent that it would be very difficult to reduce the area used to return the air to the Knowles Island exhaust raise, without seriously affecting ventilation patterns and greatly increasing power costs.

The observations taken on October 8th, 1982 at the positions shown in Figure I-3 are set out in Table I-7. Barometric pressures were measured with a Negretti and Zambra aneroid barometer in this survey. The table indicates that free liquid moisture contents of 1.2 g/kg can exist in the system corresponding to visibilities of 30.3 m using the Koschmieder and Chylek equations.

Fog occurrence in October was not severe and it is expected that summer conditions can produce liquid moisture contents exceeding 2 g/kg, with visibility reduced to 15 m and less. Localized fog in areas was quite dense. It can be deduced from the large scale mechanization of the mine that Aitken particle concentrations can be expected to be high because of the large number of diesel units. This will also affect the visibility adversely.

A major problem of control of fogging at Denison is one of scale. The amount of heat required to raise the air temperature above saturation for 2,000 m³/s would be approximately 25,000 kW which would be prohibitively expensive. This calculation does not make allowance for any heat transfer to the rock.

TABLE I-7
Barometric Pressures, Temperatures and Psychrometric Properties
Denison Mines, October 8th, 1982

Station	Position	Barometric Pressure (kPa)	Wet Bulb Temperature (°C)	Dry Bulb Temperature (°C)	Moisture Content (g/kg)	Enthalpy (J/kg)	Remarks
1	Surface portal	97.0	12.8	13.3	9.4	37.1	---
2	12950	99.2	12.2	12.2	9.0	35.0	Fog
3	15 panel travelling way	99.3	13.0	13.0	9.5	37.1	Fog
4	18950	100.4	13.9	13.9	10.0	39.2	Fog
5	22950 return	101.4	14.4	14.4	10.2	40.3	Fog
6	22950 west	101.5	13.3	15.0	8.8	37.3	Clear
7	22950 intake	101.9	12.2	14.4	7.9	34.4	Clear
8	25 panel refuge station	102.1	14.4	17.8	8.7	40.0	Clear

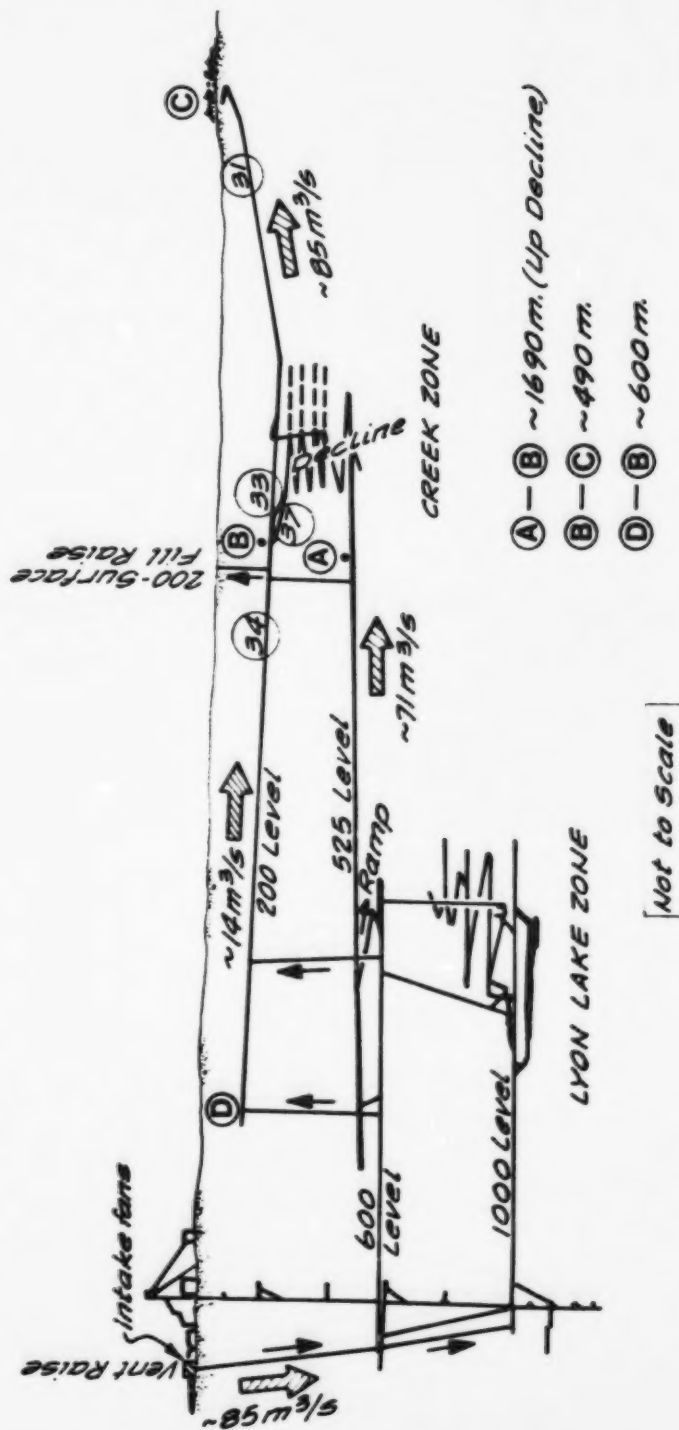
The room and pillar mining system creates a large open area which is used for the exhaust system because of the extremely large volume of air, 2400 m³/s, which is circulated through this section. The mine already maintains in excess of 1000 stoppings for air control and these are subject to damage during the twice daily blasts.

Concentration of the airflow for heating or drying will result in increasing the flow resistance and the costs of this as well as local problems resulting from the flow change are likely to be unacceptable to Denison. The operating parameters are the paramount criteria and preclude fog control measures which at this time could prove to be impractical or prohibitively expensive.

PROJECT NO 822-1578... DRAWN *hpy*... REVIEWED... DATE Jan '93

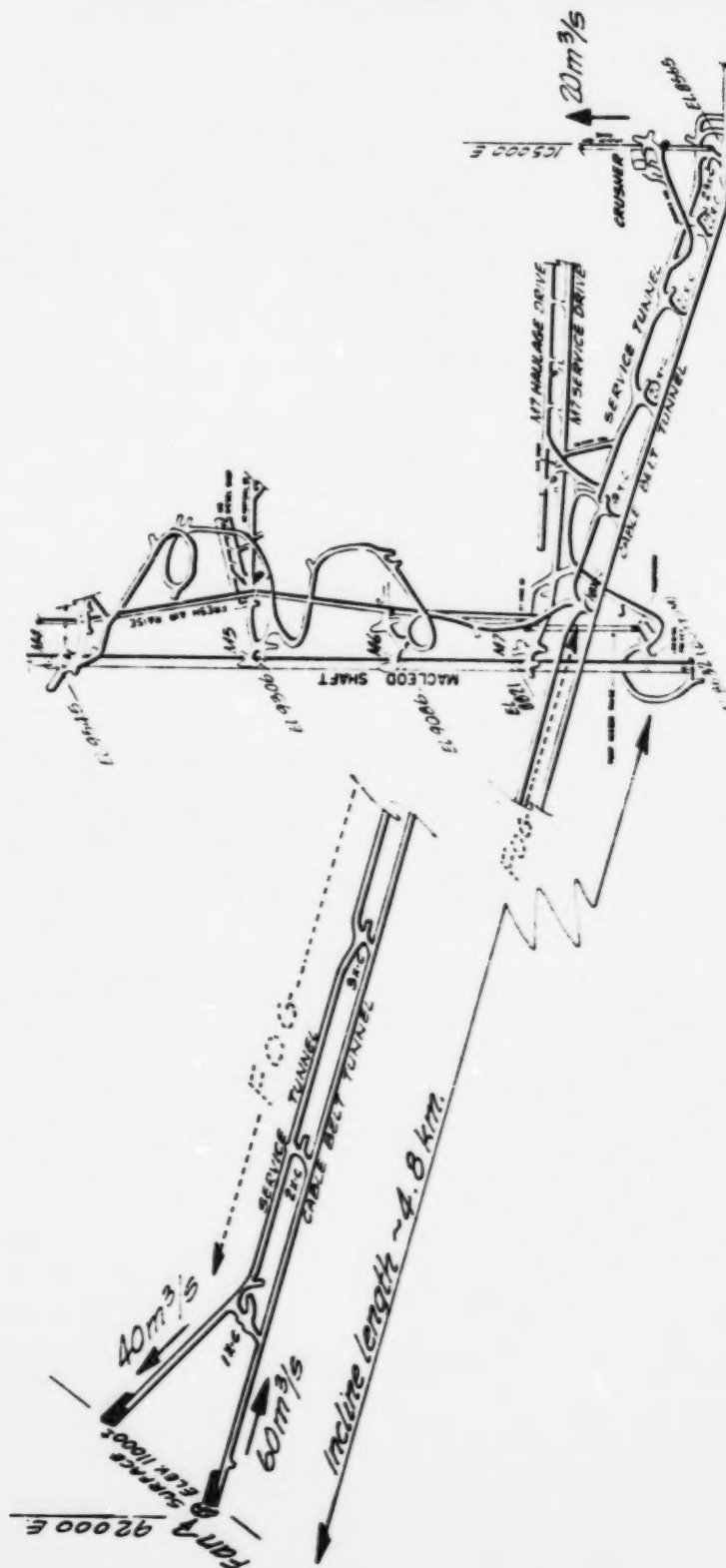
MATTABI MINE - VENTILATION SCHEMATIC

Figure I-1



PROJECT NO. 822.1578 DRAWN REVIEWED DATE 11/27/83

Schematic only..Not to scale



RIO-ALGOM
— QUIRKE MINE —

15 Panel (u/c)
 2.2×10^6 cfm

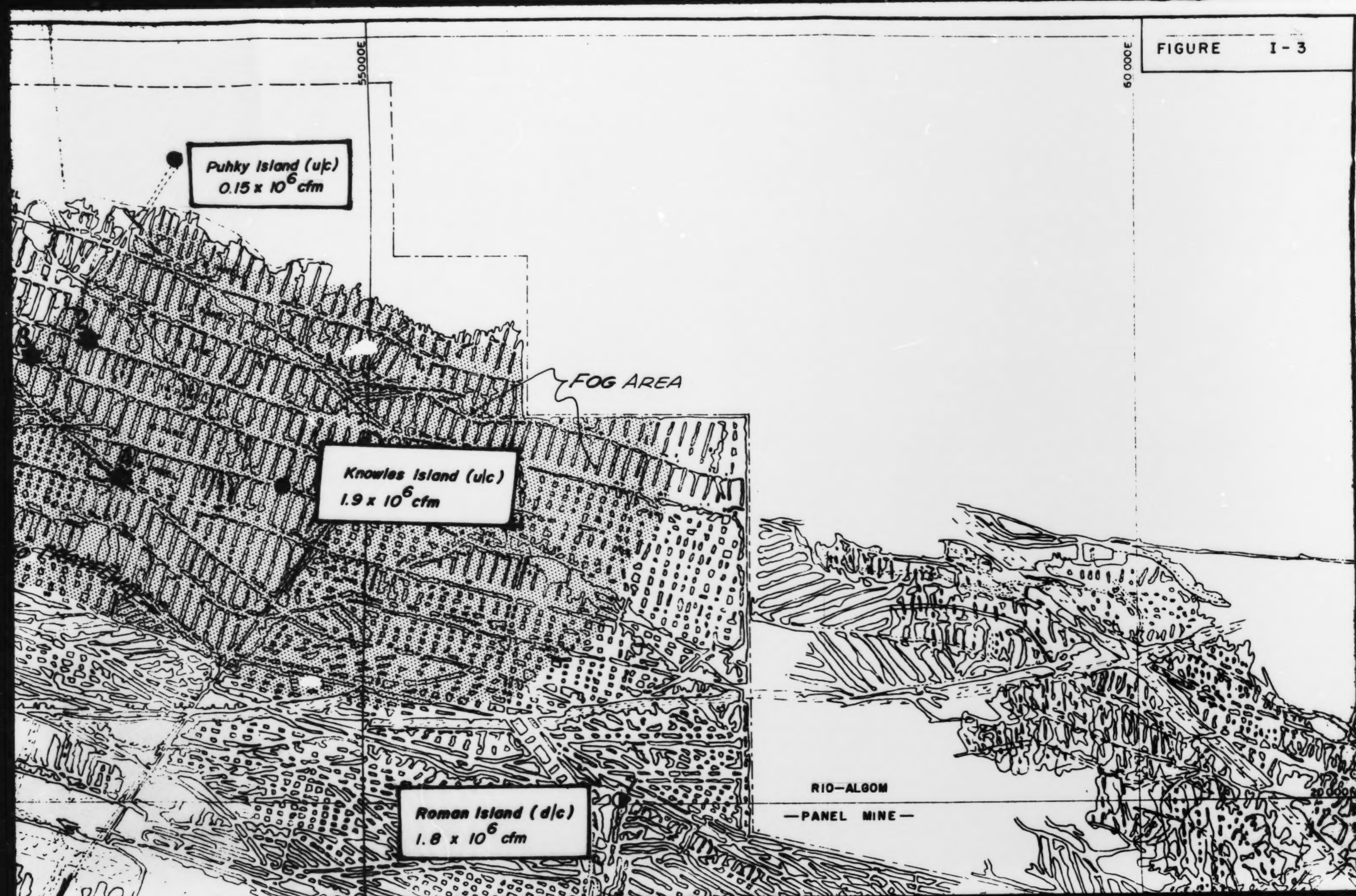
no. 1 Shaft (u/c)
 0.03×10^6 cfm

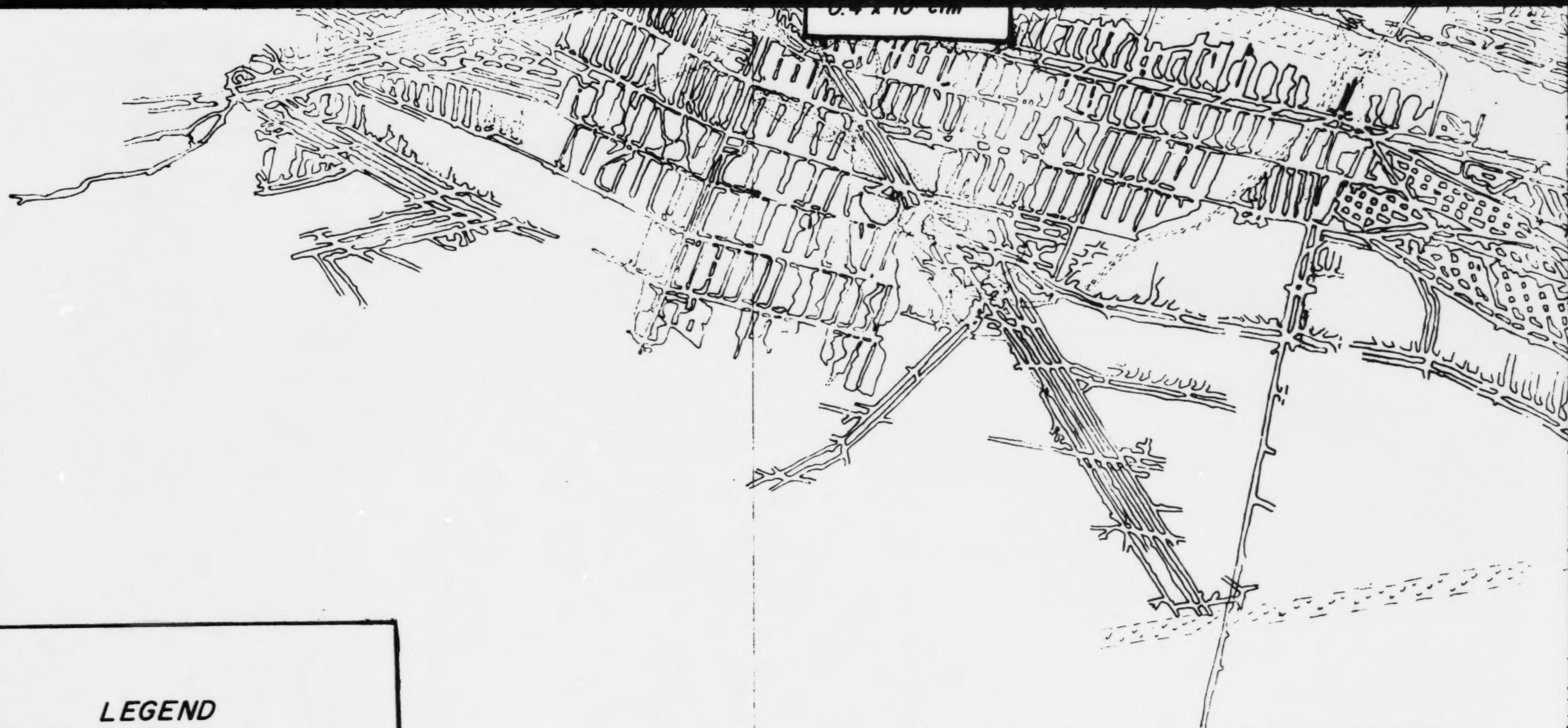
North West Raise (d/c)
 1.4×10^6 cfm

South West Raise (d/c)
 0.89×10^6 cfm

no. 2 Shaft (d/c)
 0.4×10^6 cfm

20 000 N





LEGEND

Measurement Points referred to
in Table I-7

Downcast (d/c)

Upcast (u/c)



RIO-ALGOM
— SPANISH AMERICAN MINE —

15 000N

DENISON MINES LIMITED
ELLIOT LAKE ONTARIO

DRAWN BY	ENGINEERING	RB
CHECKED BY	GEOLOGY	APPROVED

DATE Feb 11, 83

SCALE 1" = 500

REF.
REF.
REF.

Roman Island (d/c)
 1.8×10^6 cfm

— PANEL MINE —

Canmet (u/c)
 0.2×10^6 cfm

RIO-ALGOM
SH AMERICAN MINE —

— STANROCK DIVISION —

Golder Associates - June 1983

15000N

No1 SHAFT - No2 SHAFT 500 SCALE

REV. No. & DATE

TITLE

VENTILATION SHAFTS

FILE No.

DRAWING NUMBER

REV.

I - 3



Photograph 1

Swirling fog in decline at Mattabi



Photograph 2

Fog in haulage at top of Lyon Creek zone. Note vehicle headlight barely discernible.



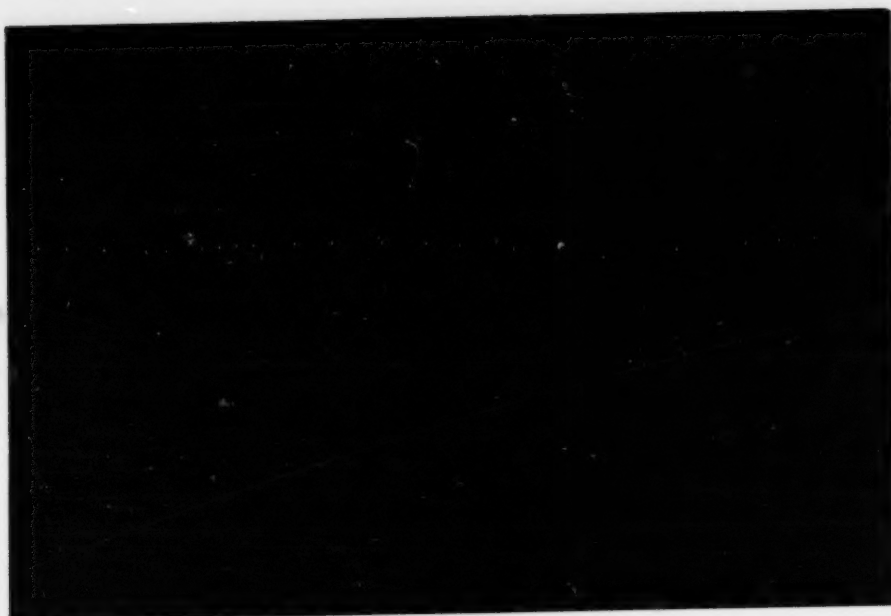
Photograph 3

Fog in haulage at top of Lyon Creek zone. Note swirling fog and vehicle headlights.



Photograph 4

Decline portal at Mattabi, showing fog being discharged.



Photographs 5 and 6

Fog in service decline at Algoma Ore Division. Note difficulty in seeing white reference line on sidewalls.

APPENDIX II

Questionnaire

QUESTIONNAIRE

A questionnaire was prepared and is included in this appendix. It was sent to 18 mines in order to determine whether fog problems were experienced.

Replies were received from 11 the mines. This represents a return of 60 per cent. Many of the mines have been affected by temporary closures which will account for some of the lack of response.

The following mines indicated that they experience fog:

- (1) Echo Bay Mines - Lupin Operation, N.W.T.
- (2) Cominco Ltd. - Con Mine, Yellowknife, N.W.T.
- (3) Canada Wide Mines Ltd. - Granduc Mine, Stewart, B.C.
- (4) Newfoundland Zinc Mines Ltd., Daniel's Harbour, Newfoundland

Echo Bay Mines - Lupin Operation

The mine is totally in permafrost and the ventilation air is not heated. Winter air temperatures are between -20 and -50°C. When the cold ventilation air meets moist air, there is immediate cooling and fog formation. Fog occurs in stopes, drifts, haulages, ramps, and return airways. The fog reduces visibility but not significantly and no special measures are required.

Some fog formation was also experienced due to moisture contained in compressed air used for drilling. The moisture contained in this air supersaturates the ventilation air when exhausted from the pneumatic drill. However, the mine now uses hydraulic drilling equipment.

The cold air fog occurs on the upper mine levels and the compressed air on the lower levels, as shown in Figure II-1.

Cominco - Con Mine, Yellowknife

The Con Mine experience some fog over the whole year in exhaust areas on 1300 level and on the 2300 level in winter. The fog is caused by warm moist exhaust air moving up into cooler areas of the mine. The deepest part of the workings is 1433 m (4700 ft.) below sea level and the foggy areas are 213 to 396 m (700 to 1300 ft) below sea level.

The area where the fog is experienced is remote from the main production areas and is not normally worked in. For this reason, no major problems are experienced and no special measures are taken because of fog, see Figure II-2.

Canada Wide Mines - Granduc Mine

Small problems are experienced with localized fogging at Granduc Mine (see Figures II-3 and II-4):

Fogging occurs in the main access tunnel in 'plugs' associated with the opening and closing of the ventilation doors at the entrance. When the door is open, air is recirculated through the fan adding heat which increases moisture contents. When the door is closed, a 'plug' of fog forms and travels through the tunnel. The problem is a minor, localized one and no special measures are taken.

An air mass from the lower levels of the mine mixes with a warmer air flow creating localized fogging which is dissipated by the addition of further air flows. The localized fogging does create a problem of water condensing on electrical gear, although visibility is not a problem. A future change in the ventilation circuits will prevent this occurrence.

Water scrubbers used as exhaust conditioners on Volvo BM trucks can cause serious visibility problems, especially on ramps. Replacement by

in-line catalytic scrubbers would interfere with combustion performance because the engine is turbo-charged. To date, the problem has been tolerated.

Newfoundland Zinc Mines

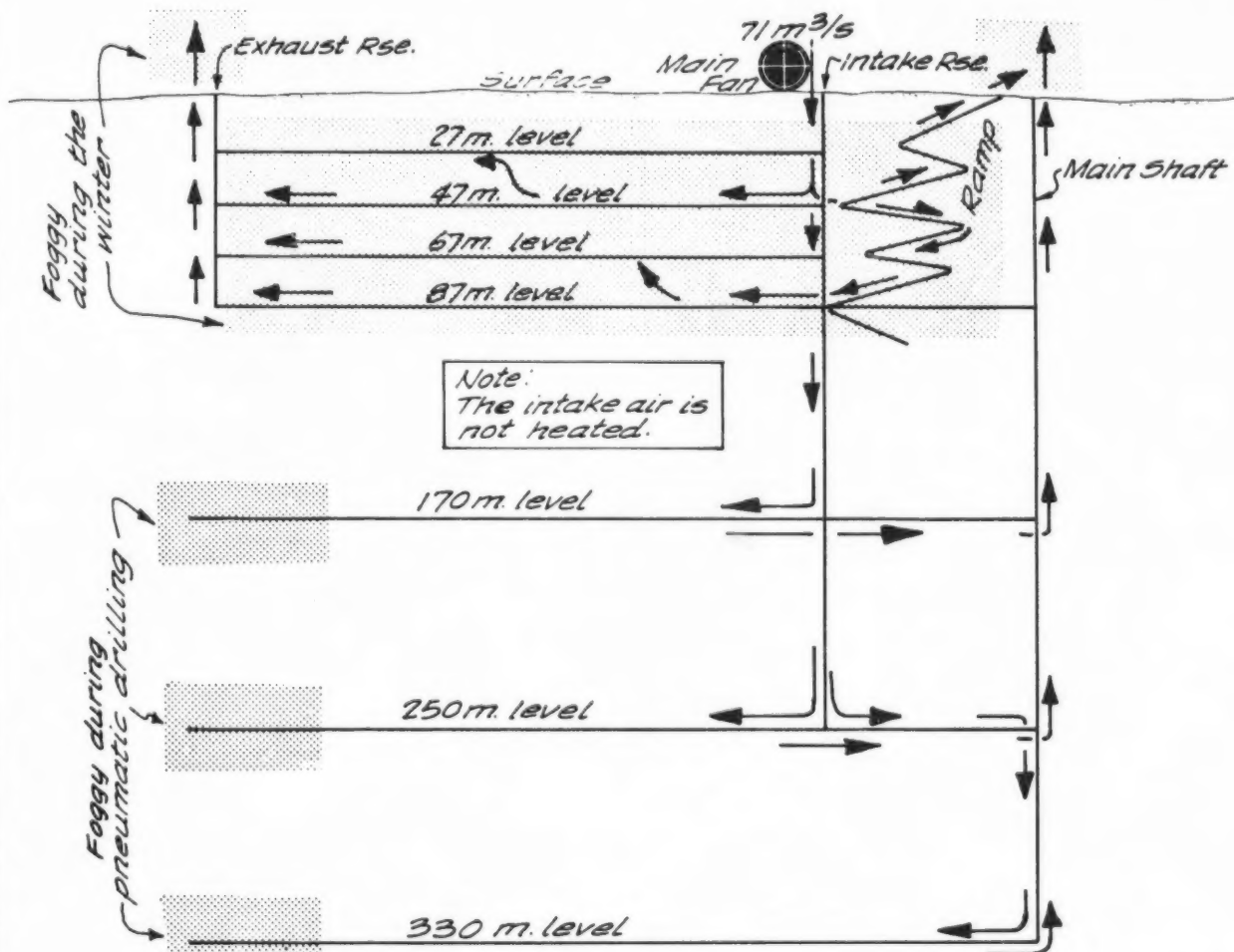
The mine experiences fog at many different barometric pressures and temperatures. The least fog occurring during summer. The fog mostly occurs in return airways due to cooling of humid air as its velocity decreases on passing from a small to larger cross section of the airway. The fog reduces visibility and amber lights are used to outline narrow areas and an upcast fan is used to mix the air discharge through the return and increase the air pressure and enthalpy to prevent supersaturation, see Figure II-5.

1. Mine name and address:
.....
.....
.....
2. Contact person and phone number:
.....
3. Do you experience fog in your underground workings?
Yes No
4. When does the fog occur? (Please circle appropriate times)
0 - 6 a.m. 7 - 12 1 - 6 p.m. 7 -12 p.m.
Working days Holidays Weekends
Jan Feb Mar Apr May June July Aug
Sept Oct Nov Dec
5. Where does the fog occur?
a) stopes
b) drifts and haulages
c) ramps
d) return airways
e) intake airways
f) shafts
g) other - please specify
.....
.....
6. Cause of fog formation, if known
.....
.....
.....
7. Average barometric pressure and air wet and dry bulb temperature
on surface, when fog occurs
.....
.....
8. Surface elevation
.....

9. Air temperatures and elevation at deepest part of workings
.....
10. Air temperatures and elevation of foggy areas
.....
.....
.....
11. Rock temperatures measured in mine at deepest level (and in foggy
areas, if applicable)
.....
.....
.....
12. Rough sketch of ventilation system and air quantities. (Please
attach to questionnaire.)
13. Rough sketch of ventilation system and air quantities in the fog
affected part of the mine. (Please attach to questionnaire.)
14. Brief details of any problems resulting from fog, such as produc-
tion loss, reduced visibility for equipment operators, etc.
.....
.....
.....
.....
15. Are any special measures used to reduce or prevent fogging. If
so, please explain in detail
.....
.....
.....
.....
16. Any additional comments or information will be welcome
.....
.....
.....
.....

VENTILATION SCHEMATIC OF LUPIN MINE

Figure II - I



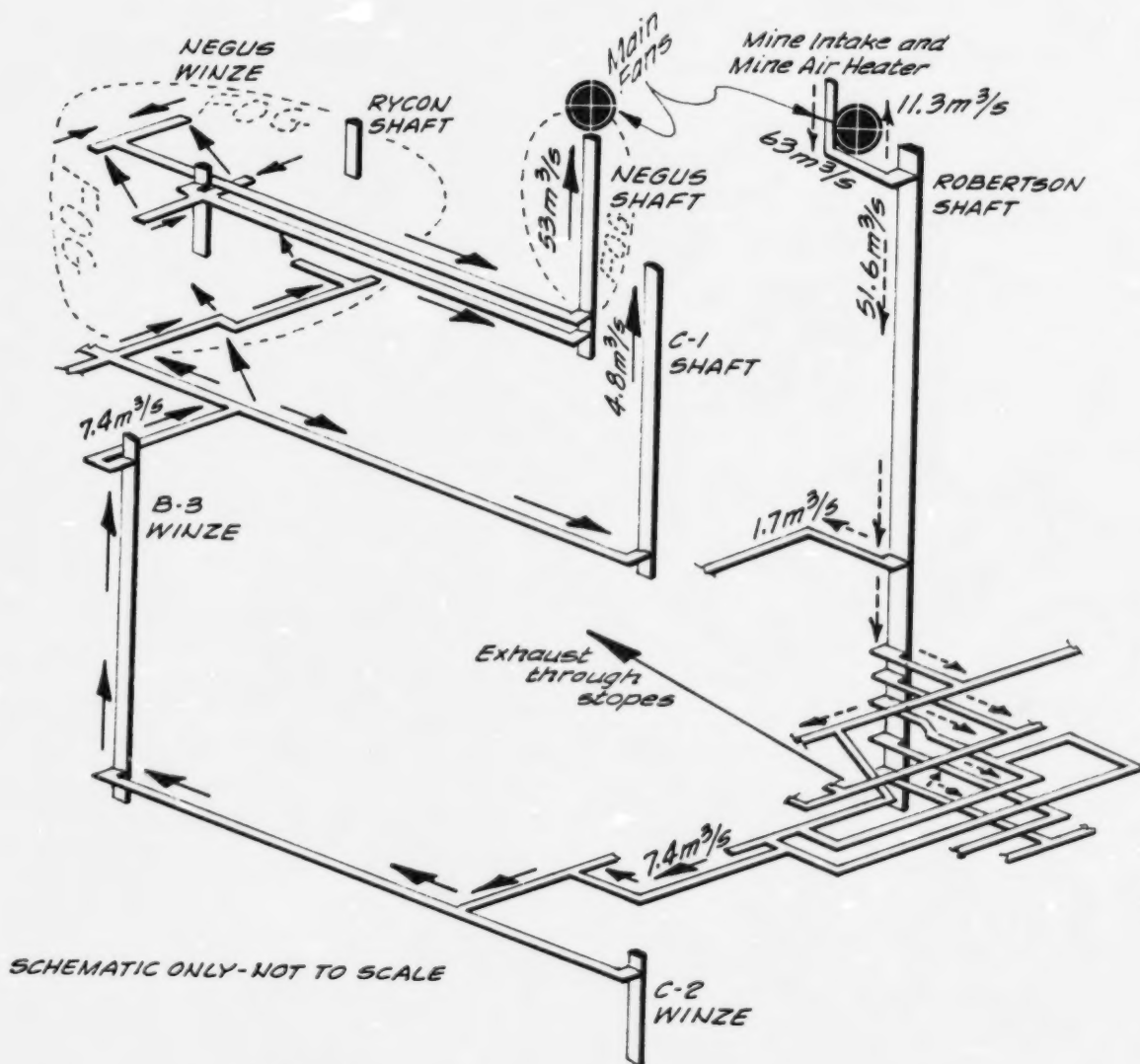
LUPIN 1982 NOV.

Schematic only - Not to Scale

PROJECT NO. 822-1578 DRAWN: JMA. REVIEWED: DATE: Jan '83

VENTILATION SCHEMATIC OF THE CON MINE

Figure II-2



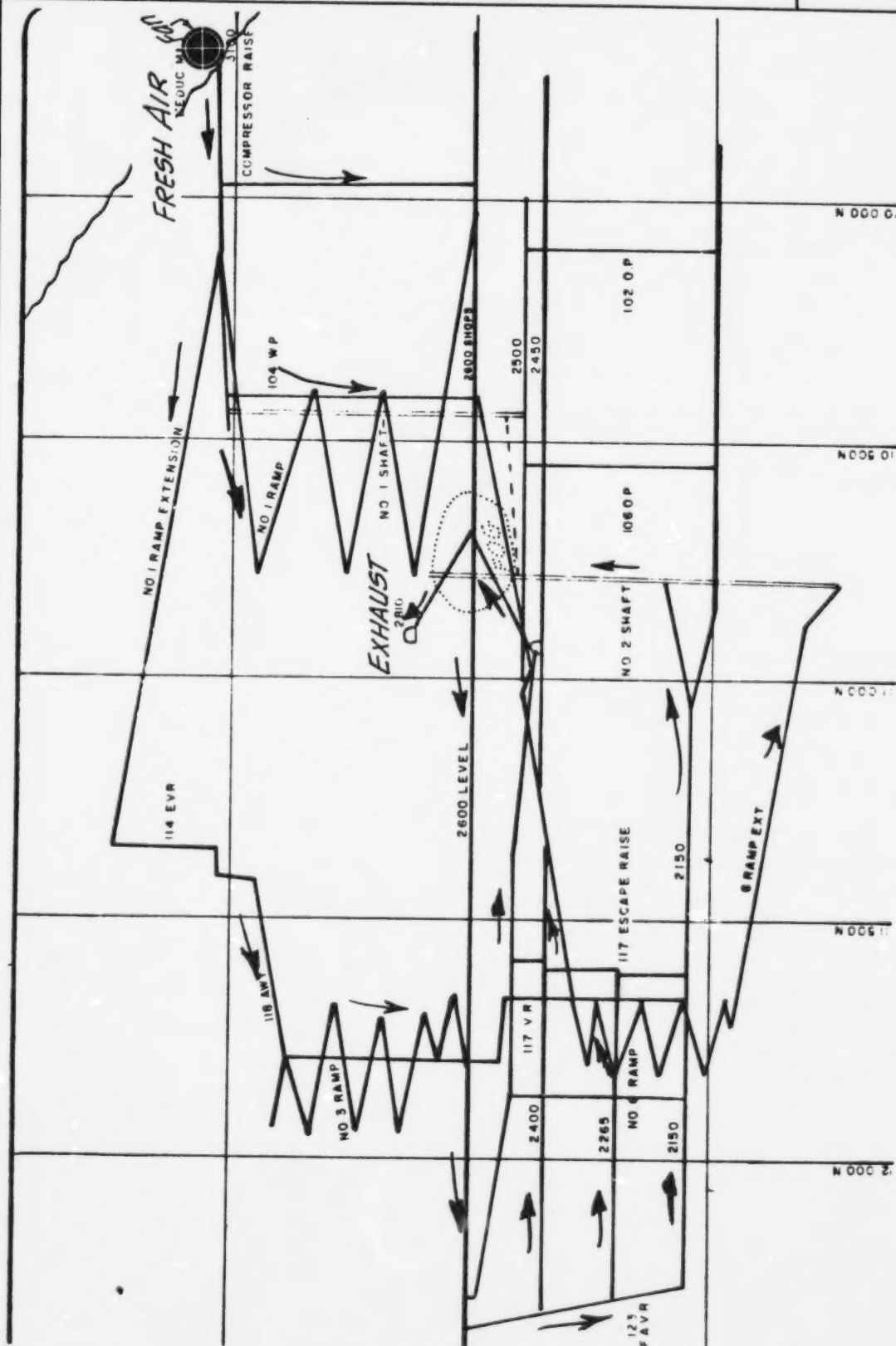
LEGEND

- Exhaust Air Flow
- Intake Air Flow

PROJECT NO. 822-1578 DRAWN 1/77 REVIEWED DATE Mar '83

LONGITUDINAL SECTION OF VENTILATION SCHEMATIC FOR GRANDUC MINE.

Figure II - 3



VENTILATION SCHEMATIC

FRESH AIR
EXHAUST AIR

CANADA WIDE MINES LTD.
GRANDUC MINE

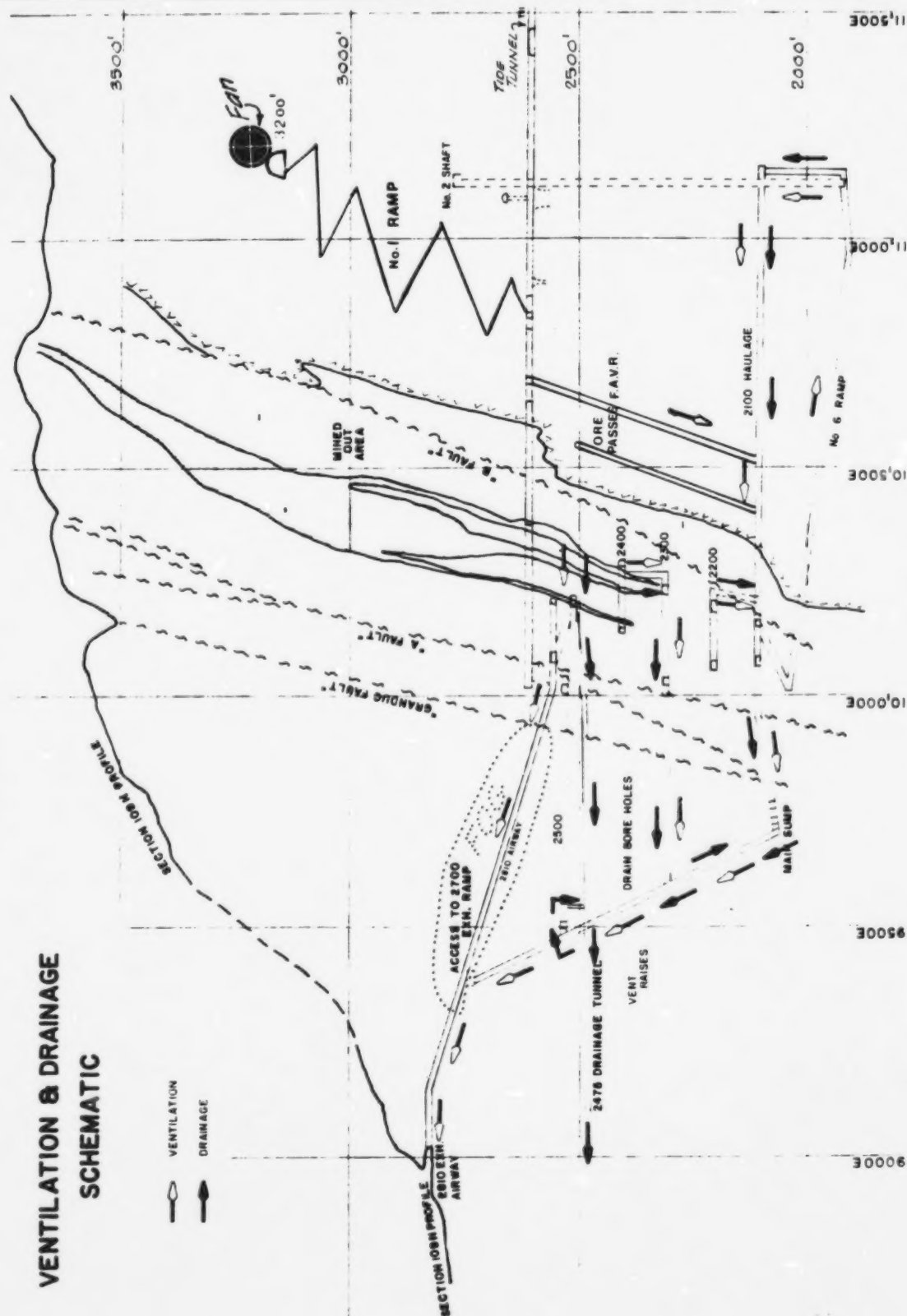
Golder Associates

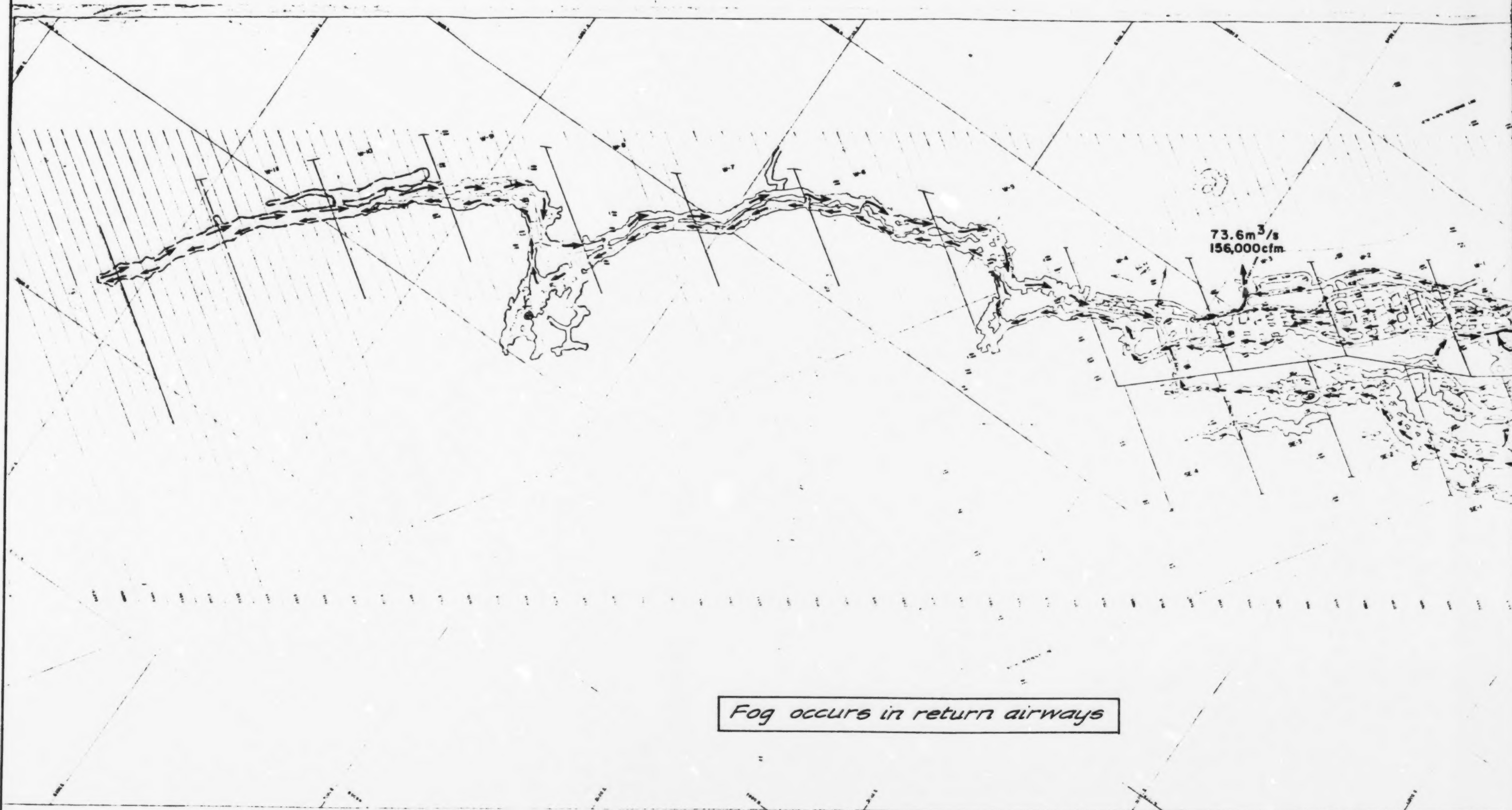
PROJECT NO. 822-1578 DRAWN DATE Jan '83

REVIEWED

VENTILATION AND DRAINAGE SCHEMATIC FOR GRANDUC MINE ON SECTION 109 N.

Figure II - 4

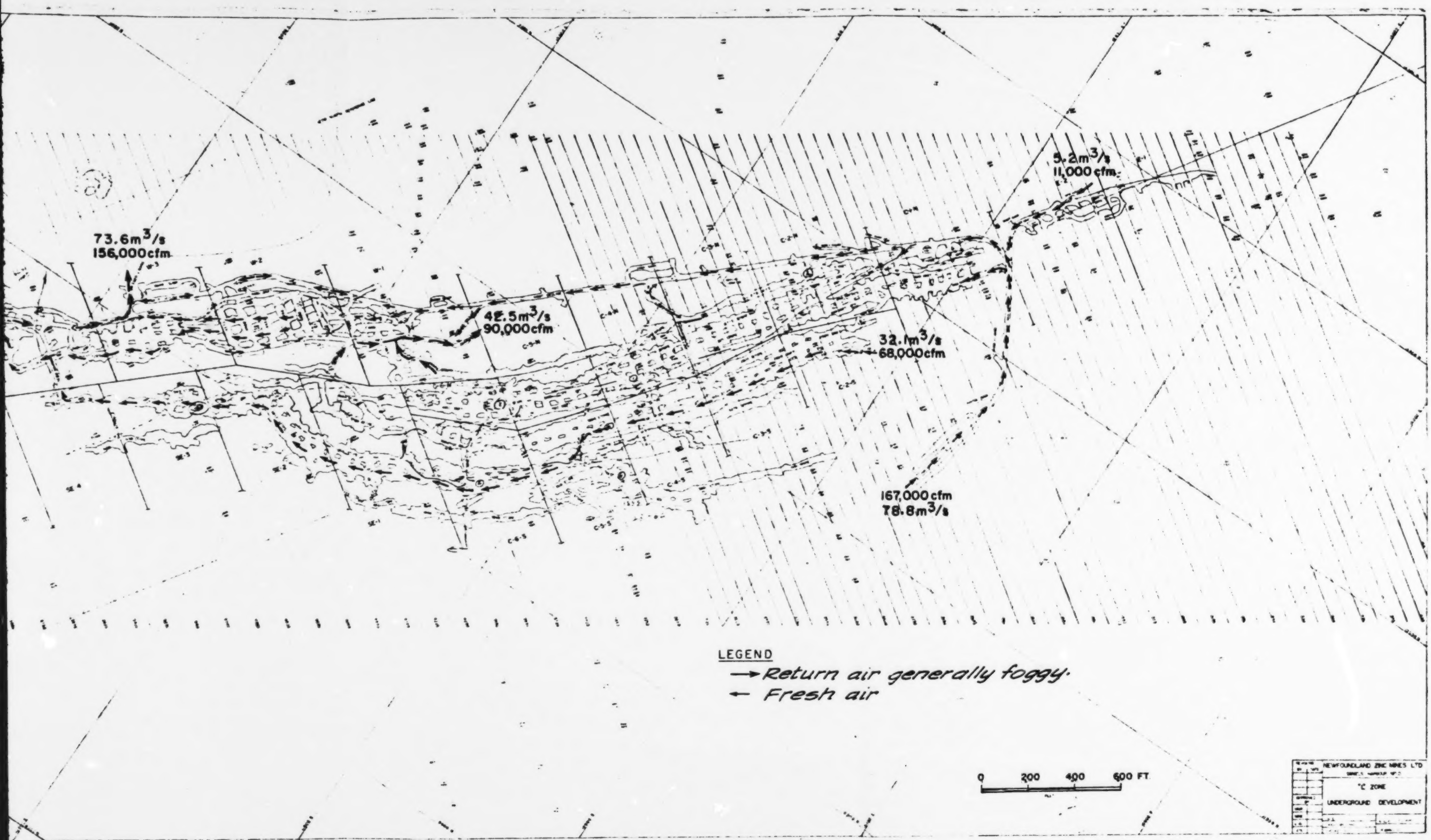




Fog occurs in return airways

NEWFOUNDLAND ZINC MINES LTD.
VENTILATION SCHEMATIC

Figure II-5



APPENDIX III

Listing Psychrometric Chart Program

PSYCHROMETRIC-CALCULATION-PROGRAM

WRITTEN BY A.E.HALL-MINERAL ENGINEERING DEPT. -JUNE 1979

PROGRAM CALCULATES PROPERTIES OF ATMOSPHERIC AIR FROM BAROMETRIC PRESSURE AND AIR TEMPERATURES

FORMAT STATEMENTS

```

1 FORMAT(1X,'PSYCHROMETRIC CHART PROGRAM-ENTER VALUES AS REQUESTED')
2 FORMAT(1X,'WET BULB TEMPERATURE-EG 24.25 OC. ENTER MINUS NUMBER TO
  1END RUN')
3 FORMAT(F10.2)
4 FORMAT(1X,'DRY BULB TEMPERATURE-OC EG 34.08')
5 FORMAT(1X,'BAROMETRIC PRESSURE-KILOPASCALS EG 102.75')
6 FORMAT(1X,'WET BULB CANNOT EXCEED DRY BULB TEMP-CHECK AND RE-ENTER
  1 DATA')
7 FORMAT(1X,'VALUE OUT OF RANGE 0-70 OC OR 70-130 KPA CHECK VALUE AN
  1D RE-ENTER DATA')
8 FORMAT(25X,'PSYCHROMETRIC DATA')
9 FORMAT(25X,'.....')
10 FORMAT(1H)
11 FORMAT(1X,'WET BULB TEMP',3X,'DRY BULB TEMP',3X,'PRESSURE-KPA',3X,
  1'RELATIVE HUMIDITY%')
12 FORMAT(3X,F6.2,9X,F6.2,9X,F7.2,9X,F9.4)
13 FORMAT(20X,'DRY AIR BASIS(KG-KG OF AIR)')
14 FORMAT(20X,'.....')
15 FORMAT(1X,'MOIST CONT',5X,'SIGMA HEAT',5X,'ENTHALPY',8X,'DEW POINT
  1 TEMP')
16 FORMAT(3X,'G/KG',10X,'KJ/KG',10X,'KJ/KG',15X,'OC')
17 FORMAT(1X,F8.4,6X,F9.4,6X,F9.4,11X,F6.2)
18 FORMAT(1X,'AIR DENSITY',3X,'SPEC VOL',8X,'VAIR APP',7X,'VAIR APP S
  1SPECIFIC')
19 FORMAT(3X,'KG/M3',8X,'M3/KG',10X,'DENS KG/M3',5X,'VOLUME M3/KG')
20 FORMAT(1X,F7.5,8X,F7.5,9X,F7.5,9X,F9.5)
21 FORMAT(20X,'VAIR BASIS (KG-KG OF VAIR)')
22 FORMAT(20X,'.....')
23 FORMAT(1X,'MOIST CONT',12X,'DENSITY',12X,'APP SPECIFIC VOL')
24 FORMAT(3X,'G/KG',17X,'KG/M3',17X,'M3/KG')
25 FORMAT(1X,F8.4,14X,F7.5,14X,F7.5)

```

CONVERSATIONAL MODE INPUT PROGRAM CHECKS INPUT VALUES

```

WRITE(6,10)
WRITE(6,1)
WRITE(6,10)
WRITE(6,2)
READ(5,3) WTEMP
IF(WTEMP.LT.0.0)GOTO 500
IF(WTEMP.GT.70.0)GOTO 200
WRITE(6,10)
WRITE(6,4)
READ(5,3)DTEMP
IF(DTEMP.LT.0.0.OR.DTEMP.GT.70.0)GOTO 200
WRITE(6,10)
IF(WTEMP.GT.DTEMP)GOTO 300
WRITE(6,5)
READ(5,3)BAR
IF(BAR.LT.70.0.OR.BAR.GT.130.0)GOTO 200

```

```

WRITE(6,10)
GOTO400
200 WRITE(6,7)
    WRITE(6,10)
    GO TO 100
300 WRITE(6,6)
    WRITE(6,10)
    GOTO100
C
C CALCULATION OF PSYCHROMETRIC PROPERTIES AS PER BARENBRUG, A.W.T.
C PSYCHROMETRY AND PSYCHROMETRIC CHARTS-3RD EDITION
C CHAMBER OF MINES OF SOUTH AFRICA, JOHANNESBURG 1974
C
400 E1=0.6105*EXP((17.27*WTEMP)/(WTEMP+237.3))
    E2=0.6105*EXP((17.27*DTEMP)/(DTEMP+237.3))
    E=(E1*(371.4+0.24*DTEMP-0.6*WTEMP)-0.24*(DTEMP-WTEMP)*BAR)/(371.4+
10.04*DTEMP-0.4*WTEMP)
    R1=100*E/E2
    R2=(622*E)/(BAR-E)
    R3=BAR/(0.287045*(273.15+DTEMP))
    R4=(BAR-E)/(0.287045*(273.15+DTEMP))
    R5=1/R3
    R6=1/R4
    S=1.005*DTEMP+(2.501-0.002387*WTEMP+0.001884*(DTEMP-WTEMP))*R2
    H=S+0.004187*WTEMP*R2
    S1=237.3*ALOG(E/O.6105)/(17.27-ALOG(E/O.6105))
    S2=622*E/(BAR-O.378*E)
    S3=(BAR-O.378*E)/(O.287045*(273.15+DTEMP))
    S4=1/S3
C
C PRINT OUT INSTRUCTIONS
C
C
WRITE(6,8)
WRITE(6,9)
WRITE(6,10)
WRITE(6,11)
WRITE(6,12)WTEMP,DTEMP,BAR,R1
WRITE(6,10)
WRITE(6,13)
WRITE(6,14)
WRITE(6,10)
WRITE(6,15)
WRITE(6,16)
WRITE(6,17)R2,S.H,S1
WRITE(6,10)
WRITE(6,18)
WRITE(6,19)
WRITE(6,20)R3,R5,R4,R6
WRITE(6,10)
WRITE(6,21)
WRITE(6,22)
WRITE(6,10)
WRITE(6,23)
WRITE(6,24)
WRITE(6,25)S2,S3,S4
WRITE(6,10)
WRITE(6,10)
GOTO 100
500 RETURN
END

```


APPENDIX IV

Conversion Tables

**Metric Practice Guide
for the
Canadian Mining
and
Metallurgical Industries**

Published by

The Mining Association of Canada

in cooperation with

The Coal Association of Canada

Edition française sur demande

February 1978
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3rd Reprint/March 1980

TABLE 9
CONVERSION FACTORS

NOTE: Conversion factors which are in bold type are exact

Multiply this	by this	to obtain
acre	0.404 685 6	hectare
acre foot	4046 856	cubic metre
acre inch	1233 482	cubic metre
ampere hour	3.6	kilocoulomb
ampere per square foot	10 763 91	ampere per square metre
ampere per square inch	0.001 550	ampere per square metre
angstrom	0.082 903 04	metre
bar	0.1	nanometre
British thermal unit (Btu)	1055 06	kilopascal
Btu per cubic foot	37 259 1	poule
Btu per cubic foot °F	67 066 1	kilopoule per cubic metre
Btu per gallon	232 08	kilopoule per cubic metre
Btu per gallon (US)	278 717	degree Celsius
Btu per hour	0.203 072	kilopoule per cubic metre
Btu per pound	2.326	kilopoule per cubic metre
Btu per pound °F	4.1868	wait
Btu per square foot, hour	3 154 60	kilopoule per kilogram
Btu per square foot, hour, °F	5.678 29	kilopoule per (kilogram degree Celsius)
Btu per ton (2000 lb)	1.163	wait per square metre
calorie (dietetic)	4.1855	degree Celsius
calorie (international)	4.1868	wait per square metre
carat (metric)	200	degree Celsius
centimetre	0.393 70	kilopoule
centimetre of mercury (0°C)	1.333 22	poule
centimetre of mercury (0°C)	0.193 37	milligram
centimetre of water (4°C)	0.393 70	inch
centimetre of water (4°C)	98 063 78	kilopascal
centimetre of water (4°C)	0.014 223	pascal
centipoise	1.0	pound per square inch
centistoke	1.0	millipascal second
chain	20.1168	square millimetre per second
cord (stacked wood - 128 ft ³)	506.7	metre
cubic centimetre	3 6246	metre
cubic centimetre	0.001	square micrometre
cubic centimetre	0.061 02	cubic metre
cubic centimetre	0.035 195	cubic decimetre
cubic centimetre	1.0	cubic inch
cubic centimetre	0.001	ounce (fluid)
cubic decimetre	61 0237	millilitre
cubic decimetre	1.8	litre

Multiply this	by this	to obtain
cubic decimetre	0.219 969	gallon
cubic decimetre	0.264 172	gallon (US)
cubic foot	0.028 316 85	cubic metre
cubic foot	28 316 85	litre
cubic foot per hour	0.007 865 79	litre per hour
cubic foot per minute	0.000 471 947 4	litre per second
cubic foot per minute	0.471 947 4	litre per second
cubic foot per second	0.028 316 85	litre per second
cubic foot per second	28 316 85	litre per second
cubic inch	16.387 064	cubic centimetre
cubic inch	16 387 064	cubic millimetre
cubic inch	0.016 387 064	litre
cubic metre	0.2759	cord
cubic metre	1.3080	cubic yard
cubic metre	35.3147	cubic foot
cubic metre	219.97	gallon
cubic metre	264.17	gallon (US)
cubic millimetre	0.001	cubic centimetre
cubic millimetre	61 023 × 10 ⁻⁶	cubic inch
cubic millimetre	1.0 × 10 ⁻⁶	cubic metre
cubic yard	0.764 555	cubic metre
day (mean solar)	86 400	second
decibel (sound power level)	1.8	decibel
decibel (sound pressure level)	1.8	decibel
degree (angle)	0.017 453	radian
degree (temperature) - see end of this table	0.017 453	radian
drum	1.771 845	gram
dyne	16	micronewton
eng	0.1	microjoule
foot	0.3048	metre
foot	304.8	millimetre
foot candle	10 763 91	lux
foot of water (4°C)	2 988 98	kilopascal
foot per hour	0.004 666 7	millimetre per second
foot per minute	304.8	millimetre per hour
foot per minute	0.009 08	metre per second
foot per minute	5.08	metre per second
foot per second	0.3048	metre per second
foot per second cubed (jet)	0.3048	metre per second cubed
foot per second squared	0.3048	metre per second squared
foot pound-force	1.355 818	poule
foot pound-force per minute	0.022 596 97	wait
foot pound-force per second	1.355 818	wait
gallon	0.004 546 08	cubic metre
gallon (US)	4.546 08	litre
gallon (US)	0.003 785 412	cubic metre
gallon (US)	3.785 412	litre
gallon per minute	0.075 768	litre per second
gallon per minute (US)	0.063 090 2	litre per second
gallon per day	0.004 546 08	cubic metre per day

Multiply this	by this	to obtain	Multiply this	by this	to obtain
gallon per day	0.000 052 616 8	litre per second	kilogram calorie (international)	3 9683	Btu (international)
gauss	0.1	millitesla	kilogram calorie (international)	4186 8	joule
gram	64.798 91	milligram	kilogram-force	9.806 65	newton
gram per cubic foot	2.288 352	gram per cubic metre	kilogram per cubic centimetre	36.127 282	pound per cubic inch
gram	15.432 358 3	gram	kilogram per cubic metre	1.0	gram per litre
gram	0.032 150 75	ounce (apothecary or troy)	kilogram per cubic metre	1.685 558	pound per cubic yard
gram	0.035 273 96	ounce	kilogram per cubic metre	0.010 022	pound per gallon
gram	0.002 679 2	pound (apothecary or troy)	kilogram per kilometre	1.0	gram per metre
gram	0.002 204 62	pound	kilogram per litre	1.0	gram per millilitre
gram calorie (international)	4.186 8	joule	kilogram per kilometre	0.6719 × 10 ⁻³	pound per foot
gram per cubic centimetre	62.428 7	pound per cubic foot	kilogram per kilometre	3.548	pound per mile
gram per cubic centimetre	10.022 41	pound per gallon	kilogram per metre	0.871 97	pound per foot
gram per litre	0.002 428 7	pound per cubic foot	kilogram per metre	2.015 91	pound per yard
gram per cubic metre	0.010 022 41	pound per gallon	kilogram per square centimetre	2048.16	pound per square foot
gram per cubic metre	0.436 995 7	gram per cubic foot	kilogram per square centimetre	0.204 816	pound per square inch
gram per cubic metre	1.0	milligram per litre	kilogram per square metre	0.026 839	Btu per cubic foot
gram per metre	0.000 062 428	pound per cubic foot	kilogram per square metre	0.004 309	Btu per gallon
gram per tonne	1.0	pound per cubic foot	kilogram per square metre	0.429 923	Btu per pound
gram per tonne	0.002	milligram per kilogram	kilogram per square metre	1.0	joule per litre
gram per tonne	2.471 054	pound per ton (short)	kilogram per square metre	35.315	cubic foot
hectare	10 000	acre	kilogram per square metre	219.969	gallon
horsepower (boiler)	9 809.50	square metre	kilogram per square metre	264.172	gallon (US)
horsepower (electric)	746	kilowatt	kilogram per square metre	0.621 371	mile
horsepower (electric)	6.746	watt	kilogram per square metre	0.539 96	knot
horsepower (550 ft lbf/s)	0.745 699 9	kilowatt	kilogram per square metre	0.277 778	metre per second
horsepower hour	2 684.52	kilowatt	kilogram per square metre	0.621 371	mile per hour
hundredweight (100 lb)	45.359 237	megapascal	kilogram per square metre	0.112 40	ton-force (short ton)
hundredweight (112 lb)	50.802 345	kilogram	kilogram per square metre	0.295 3	inch of mercury (0°C)
inch	2.54	centimetre	kilogram per square metre	4.014 74	inch of water (4°C)
inch	0.0254	metre	kilogram per square metre	1000	newton per square metre
inch	25.4	millimetre	kilogram per square metre	20 885.43	pound-force per square foot
inch pound-force	0.112 085	newton metre	kilogram per square metre	0.145 037 7	pound-force per square inch
inch mercury (0°C)	3.386 39	kilopascal	kilogram per square metre	9.806 65	newton
inch mercury (0°C)	25.4	millimetre of mercury	kilogram per square metre	0.947 81	Btu (international)
inch of water (4°C)	0.249 082	kilopascal	kilogram per square metre	1.340 48	horsepower (electric)
joule	0.000 947 8	Btu (international)	kilogram per square metre	3412	Btu (international)
joule	0.238 846	calorie (international)	kilogram per square metre	1.340 5	horsepower hour
joule	0.737 562	foot pound-force	kilogram per square metre	3.6	megajoule
joule	0.3725 × 10 ⁻⁶	horsepower hour	kilogram per square metre	4.448 222	kilowatt
joule	0.2778 × 10 ⁻⁶	kilowatt hour	kilogram per square metre	1.852	kilometre per hour
joule	1.0	newton metre	kilogram per square metre	6 894.757	megapascal
joule per litre	0.026 839	Btu per cubic foot	kilowatt		
joule per litre	1.0	kilopoule per cubic metre	kilowatt hour		
kilogram	32 150.75	ounce (apothecary or troy)	kilowatt hour		
kilogram	35 273.96	ounce	kilowatt hour		
kilogram	2.6792	pound (apothecary or troy)	kilowatt hour		
kilogram	2 204.62	pound	kilowatt hour		
kilogram	0.000 984 21	ton (long)	kilowatt hour		
kilogram	0.001 102 3	ton (short)	kilowatt hour		

Multiply this	by this	to obtain	dm ³		Multiply this	by this	to obtain
litre	1.0	cubic decimetre			newton metre	0.737 562	foot pound-force
litre	0.035 315	cubic foot			ounce (apothecary or troy)	31.103 476 8	gram
litre	61 023 744	cubic inch			ounce (fluid)	28.349 523	gram
litre	6.801	cubic metre			ounce-force per	28 413 062	millilitre
litre	0.219 969	gallon			square inch	0.430 922 3	kilopascal
litre	0.264 172	gallon (US)			ounce (apothecary or troy)		
litre	35.1951	ounce (fluid)			per ton (short)	34 285 71	gram per tonne or metric ton
litre	0.879 877	quart			ounce (mass) per gallon	6 236 024	gram per litre
litre per second	2 118 88	cubic foot per minute			ounce (mass) per gallon	6 236 024	kilogram per cubic metre
litre per second	13 1982	gallon per minute			yard	33 9057	gram per square metre
litre per second	15 8503	gallon (US) per minute			pascal	See kilopascal	
litre per square foot	10 763 91	lux			pent	0.568 261	litre
metre	39 370	inch			pint (US)	0.473 176	litre
metre	3 280 84	foot			pound (apothecary or troy)	373.241 721 6	gram
metre	1.0936	yard			pound	453.592 37	gram
metre of water (4°C)	3 280 84	foot of water			pound	0.453 592 37	kilogram
metre of water (4°C)	9 806 376	kilopascal			pound per cubic foot	16 018 46	gram per litre
metre of water (4°C)	1 422 29	pounds per square inch			pound per cubic foot	16 018 46	kilogram per cubic metre
metre per minute	3 280.8	foot per minute			pound per cubic inch	27 679 90	gram per cubic centimetre
metre per minute	0.054 68	foot per second			pound per cubic yard	27 679 90	kilogram per litre
metre per minute	0.037 28	mile per hour			pound foot per second	0.593 276	kilogram per cubic metre
metre per minute	196 85	foot per minute			(momentum)	0.138 255	kilogram metre per second
metre per second	3 280.8	foot per second			pound foot squared	0.042 140 1	kilogram metre squared
metre per second	2 369	mile per hour			(moment of inertia)	4.448 222	newton
metre per second	3 280.8	foot per second squared			pound-force	1 488 16	kilogram per metre
metre per second squared	1.0	siemens			pound per foot	90 776 37	kilogram per cubic metre
micrometre	0.039 370	mil			pound per gallon	119 826 4	kilogram per cubic metre
micron	1.0	micrometre			pound per gallon (US)	0.125 997 9	gram per second
mil (0.001 in)	25.4	micrometre			pound per hour	0.453 592 37	kilogram per hour
nautical mile	1.852	kilometre			pound per mile	0.281 949	kilogram per kilometre
nautical mile	1.609 344	kilometre			pound per minute	7 559 87	gram per second
nautical mile	1.609 344	metre			pound per minute	0.007 559 87	kilogram per second
nautical mile per hour	0.44764	kilometre per hour			pound per second	0.453 592 37	kilogram per second
nautical mile per hour	0.1	metre per second			pound (mass) per square foot	4 882 428	kilogram per square metre
nautical mile per hour	0.015 432	gram			pound (mass) per square inch	703 0696	kilogram per square metre
nautical mile per hour	35 274 × 10 ⁻⁶	ounce			pound-force per square foot	0.047 880 26	kilopascal
nautical mile per hour	2 204 62 × 10 ⁻⁶	pound			pound-force per square inch	47 880 26	pascal
nautical mile per hour	0.061 02	cubic inch			pound-force per square inch	6 894 757	kilopascal
nautical mile per hour	0.035 195	ounce (fluid)			pound-force per square inch	0.703 1	metre of water (4°C)
millilitre	0.039 37	inch			pound per ton (short)	8.89	kilogram per tonne
millilitre	39 37	mil			pound per yard	0.496 055	kilogram per metre
millilitre	1000	micrometre			quart	1 136 522	litre
millilitre	0.133 322	kilopascal					
millilitre mercury (0°C)	9 806 376	pascal					
millilitre water (4°C)	1 163	gigajoule per tonne					
million Btu per ton	4844.69	cubic metre per day					
million gallons per day	0.052 816 8	cubic metre per second					
million gallons per day	0.224 808 9	pound-force					

Multiply this	by this	to obtain
quart (US)	0.946 353	L
radian	180/π	degree (angle)
radian per second	30/π	revolution per minute
revolution per minute	1/(2π)	revolution per second
revolution per second	π/30	radian per second
revolution per second	2π	radian per second
square centimetre	0.1550	square inch
square centimetre	0.0001	square metre
square centimetre	100	square millimetre
square foot	0.092 903 04	square metre
square inch	6.4516	square centimetre
square inch	645.16	square millimetre
square kilometre	247.1	acre
square kilometre	100	hectare
square kilometre	0.386 10	square mile
square metre	0.0001	hectare
square metre	10 000	square centimetre
square metre	10 763 9	square foot
square metre	1 195.99	square yard
square mile	258 998 8	hectare
square millimetre	2 589 988	square kilometre
square millimetre	0.01	square centimetre
square yard	0.001 550	square inch
tesla	0.836 127 4	square metre
therm	10 000	gauss
ton (long)	105 506	megapascal
ton (long)	1016.046 908 8	kilogram
ton (register)	1.016 046 908 8	tonne or metric ton
ton (short)	2 831.685	cubic metre
ton (short)	907.184 74	kilogram
tonne or metric ton	0.907 184 74	tonne or metric ton
tonne or metric ton	1000	long ton
tonne or metric ton	0.984 206 5	short ton
tonne or metric ton	1 102.311	kilometon
ton-force (short ton)	8 896.443	kilopascal
ton-force (short ton) per square foot	95 760 514	megapascal
ton-force (short ton) per square inch	13 789 514	ton mile (short ton)
tonne kilometre	0.684 944	tonne kilometre
ton mile (short ton)	1 459.97	tonne kilometre
ton mile (long ton)	1 635.169	tonne per cubic metre
ton (short) per cubic yard	1 186.553	tonne per cubic metre
ton (long) per cubic yard	1 328.839	kilogram per litre
tonne per cubic metre	1.0	pound per cubic yard
tonne per cubic metre	1685.555	ton (short) per cubic yard
tonne per cubic metre	0.842 777	kilogram per second
tonne per hour	0.277 778	kilogram per second
ton (short) per hour	0.251 995 8	kg/s
ton (short) per hour	0.907 184 74	kg/s

Multiply this	by this	to obtain
watt hour	3.600	kilopoule
watt hour	3 412	Btu (international)
watt second	1.0	joule
watt per square foot	10 763.91	watt per square metre
yard	0.9144	metre

TEMPERATURE CONVERSIONS

degree Celsius	+273.15	= kelvin
degree Celsius	(°C × 9/5) + 32	= degree Fahrenheit
degree Fahrenheit	+459.67	= degree Rankine
degree Fahrenheit	(°F - 32) × 5/9	= degree Celsius

Conversion factors which are in bold type are exact.

9. RULE OF THUMB CONVERSIONS

Following is Table 10, listing some approximate conversion (rule of thumb) factors. These factors are recommended for use only where an approximation is desired or as a means of performing a quick check on a detailed calculation.